Optimizing yield while minimizing phosphorus water quality impacts: Some do's and don'ts

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Nutrient management and water quality issues

Public concerns about agriculture impacts on water quality and the likelihood of further regulation have been increasing. The uninformed public and many in 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 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). Eutrophication of Iowa streams and lakes as well as waters of the Gulf of Mexico due to nutrient-induced excess algae growth is a real or perceived problem. Therefore, producers and crop advisors should know fundamental concepts of soil testing use and P application practices and their relationships to both crop yield and water quality. They must 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 for any nutrient.

Agronomic considerations for P management

Soil phosphorus testing is a very useful diagnostic tool

Soil testing for P 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 well justified. Soil-test methods attempt to measure an amount of nutrient that is proportional to the amount of nutrient available for crops. The concentration of nutrient measured may differ across soils with contrasting properties and different test methods for a specific nutrient often provide different results that can be expressed in a variety of ways. Therefore, all 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. Iowa and most states establish soil-test interpretation categories that encompass very low to very high nutrient levels. In Iowa we have had extensive field calibration research for P in corn and soybean over the years. As the soil-test levels increase, the probability of a yield increase from fertilization and the size of the yield or economic response decrease (Fig. 1).

There are many potential sources of error in soil testing that range from sampling error in the field, analytical error, and uncertainty about the crop-availability estimate. Although useful, therefore, there is always some degree of uncertainty in soil testing. Relationships such as in Fig. 1 show well the degree of uncertainty that always exists when relating soil-test values with crop response to fertilization. Sampling error due to large spatial variability is very high and laboratory error is possible, so both 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 the probability of response for the different soil-test categories. In Iowa, the percentage of P 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.

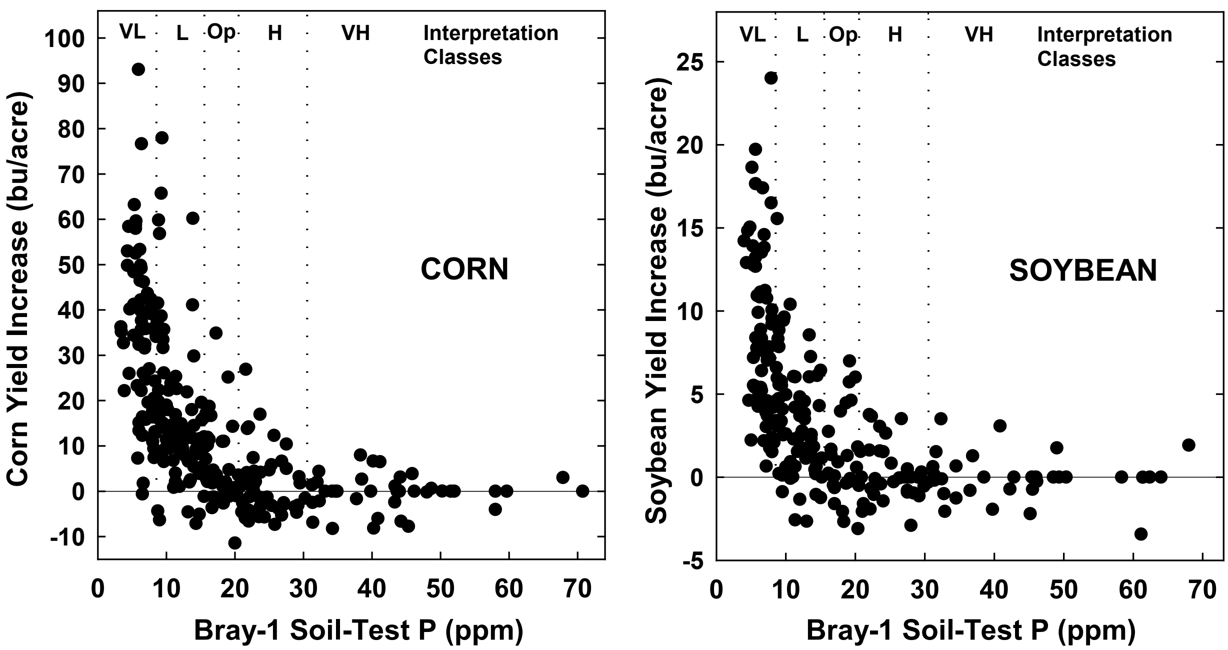

Figure 1. Relationship between grain yield increase from fertilization and soil-test P. Data points adapted from Dodd and Mallarino (2005) and soil-test P interpretation classes from extension publication PM 1688 (Mallarino et al., 2013).

The P application rates for low-testing soils recommended in Iowa are based on crop response data, and are designed to be profitable and to minimize risk of yield loss this soil-test range where the probability of a large crop response is very high. These rates will gradually increase soil-test P to the Optimum category, for which the fertilizer recommendation is designed to maintain an Optimum level based on estimates of P 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 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 into unavailable forms as may happen in other regions. Most soils retain P, but this does not mean retention (or fixation) in forms unavailable to plants. Although studies suggest that 20 to 30% of the applied P is absorbed by a first crop, the rest of the absorbed P comes from a soil pool consistent of native P and residual P from pervious applications. Therefore much of the applied P can be "banked" in the soil, which allows for long-term soil-test and fertilizer management. This is not possible for N, and may not be an efficient practice for P in regions where a major proportion of the applied P is retained by soil in forms of low crop availability.

What soil-test level should be maintained?

Fertilizer or manure application and P removal with crop harvest are the most important factors determining change in soil-test levels over time in soils of Iowa. 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 rates equivalent to crop removal as long as assumed yield levels and nutrient concentrations of harvested products are appropriate. However, the relationship between P removal and soil-test P is clear and consistent only over a period of years and can be very variable from year to year. Research has shown that variation in yield levels do not affect soil-test critical levels, at least at the highest yield levels currently observed in Iowa, but consideration of the yield level and removal is very important to maintain soil-test values.

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 indicate that the objective of fertilization based on removal is to maintain a soil-test range (Optimum) that results in about 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 P application is small in one year (1 to 2 ppm) and gradual over time. Therefore, 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. Also, perceptions about next year crop and fertilizer prices may encourage producers to apply no maintenance fertilization or a buildup rate.

Considering crop/fertilizer price ratios, uncertainty, and land tenure

The crop and fertilizer price ratio influence the fertilizer rate that should be applied in order to optimize the profitability of fertilizer application and crop production. The net returns to investment in fertilizer are high in low-testing soils, decrease as soil-test levels increase, and may become negative for the High and Very High test categories. Fertilization of low-testing soils usually results in large returns and the probability of a large yield increase is very high. Iowa experimental results in Fig. 2 show how net returns to fertilization with a certain rate change according to soil-test values for two price ratios.

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

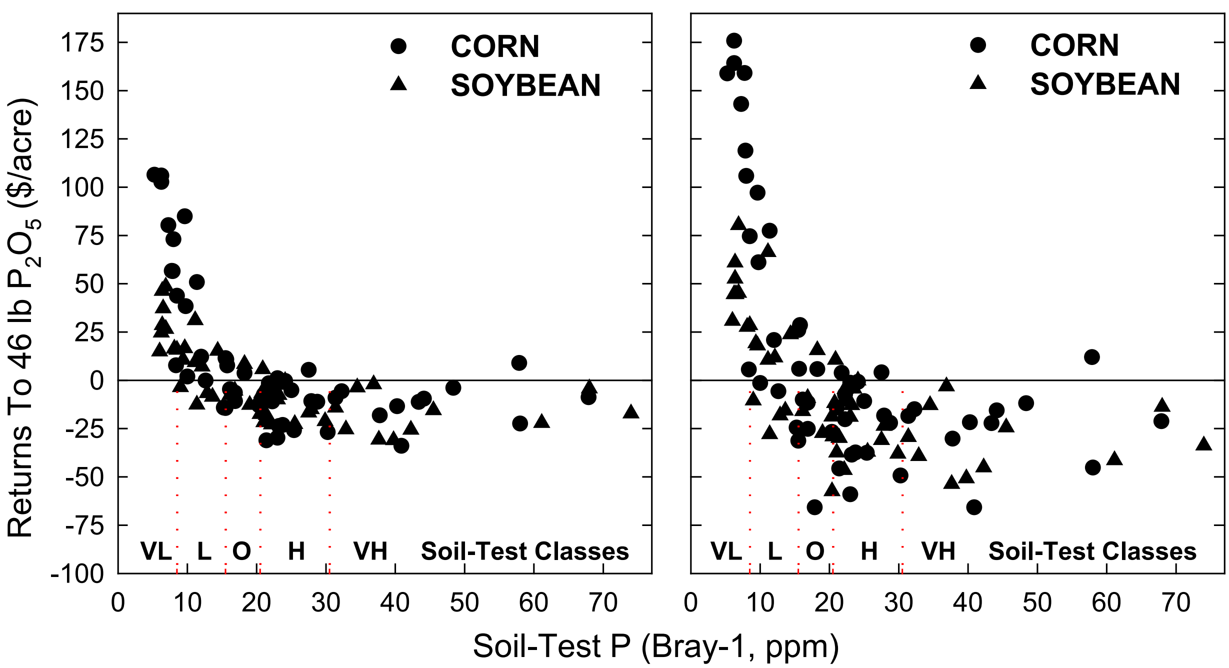

Figure 2. Net returns to P for different soil-test P levels and prices. A: Corn and soybean grain at \$2.00/bu and \$5.50/bu, and P at \$0.32/lb P_2O_5. B: Corn and soybean at \$4.00/bu and \$10.00/bu, and P at \$0.40/lb. VL, very low; L, low, O, optimum; H, high; VH, very high. (Mallarino, 2010).

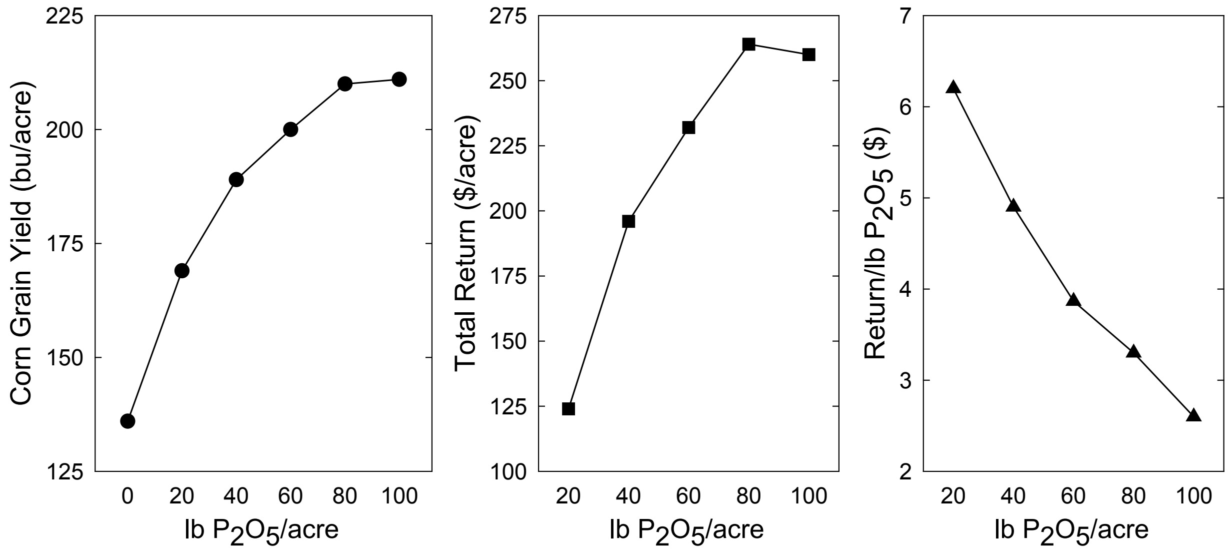

Figure 3. Corn yield response to P fertilization in a soil testing very low in P, total net returns, and returns per lb of P2O5 applied. Data assumed $4.00/bu of corn and $0.40/lb P2O5 (Mallarino, 2010).

A low application rate may increase the return per pound of P applied but may limit yield, total return to investment in fertilizer, and total return to the production system. As the soil-test level increases and the magnitude and probability of crop response decrease, the penalty and risk from over-applying fertilizer is much higher. In high-testing soils, the likelihood of a loss to investment in fertilization is high because the probability of a yield response is low and any response is small. Allowing a soil-test decline in high-testing soils also will reduce the risk of water quality impairment. Therefore, avoiding unnecessary fertilization of high-testing soils is the easiest and most profitable change a producer can implement with little or no risk.

Land tenure and the producer business management approach strongly influence the amount of P to be applied with soil-test P at the optimum level. Many years ago Fixen (1992) demonstrated that interest rates and land tenure can influence the optimum soil-test P and K levels. Reducing the P fertilizer rate in low-testing soils with safe or uncertain 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. With uncertain land tenure and optimum soil-test levels, however, the fertilization rate may be reduced or withheld because of the low probability of crop response. If the reduction in the application rate is prolonged over time, however, total net returns to fertilization and future productivity may be limited.

*Phosphorus fertilizer placement method*s

A direct consequence of having soils with little P "fixation" capacity in Iowa given our soil properties and humid climate is that methods of fertilizer application or use of products that may enhance fertilizer P use efficiency do not have the value they may have in other regions. Many Iowa field trials have shown little or no difference between broadcast, banding with the planter, and deep-banding P placement methods in corn (other than starter effects in some conditions) or soybean managed with tillage, no-tillage, strip-tillage, or ridge-tillage. Data in Fig. 4 show, as an example, results for three low-testing soils managed with no-till. 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 this is seldom the case in Iowa and the humid Corn Belt. Yet, subsurface banding can be a good method to apply P uniformly and precisely, and can be used together with strip tillage, for example.

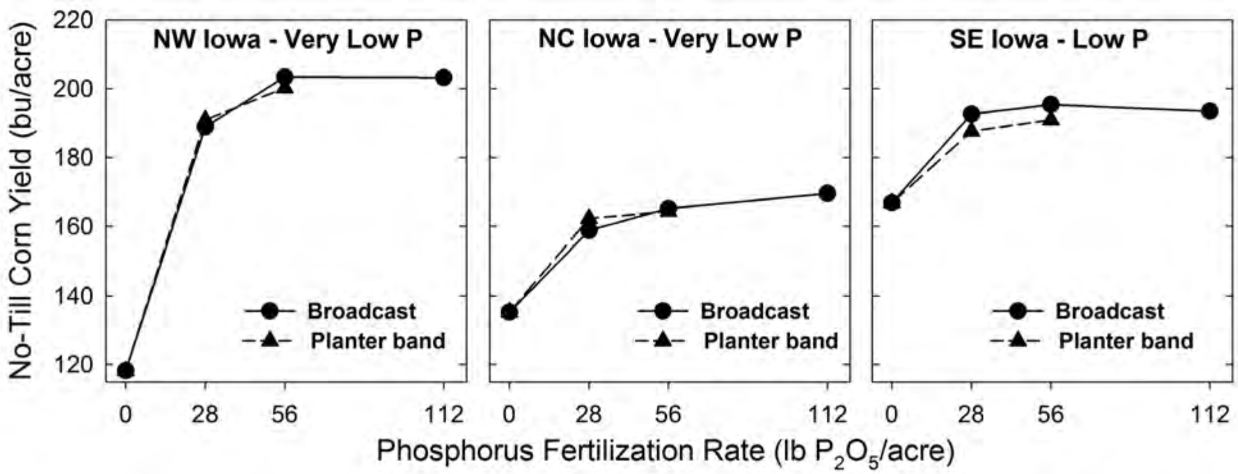

Figure 4. No-till corn response to broadcast or planter-band P placement in three long-term Iowa trials in soils testing very low or low in soil-test P (Mallarino, ISU).

Soil-test phosphorus, application rate, and source effects on water quality

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 improves the relationship compared with the common 6-inch sampling depth in both tilled and no-tilled fields. The increasing risk of P loss becomes clear and consistent for soil-test values higher than about 30 to 40 ppm (6-inch depth), which is a level slightly higher than optimum for crops. The 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 than Optimum.

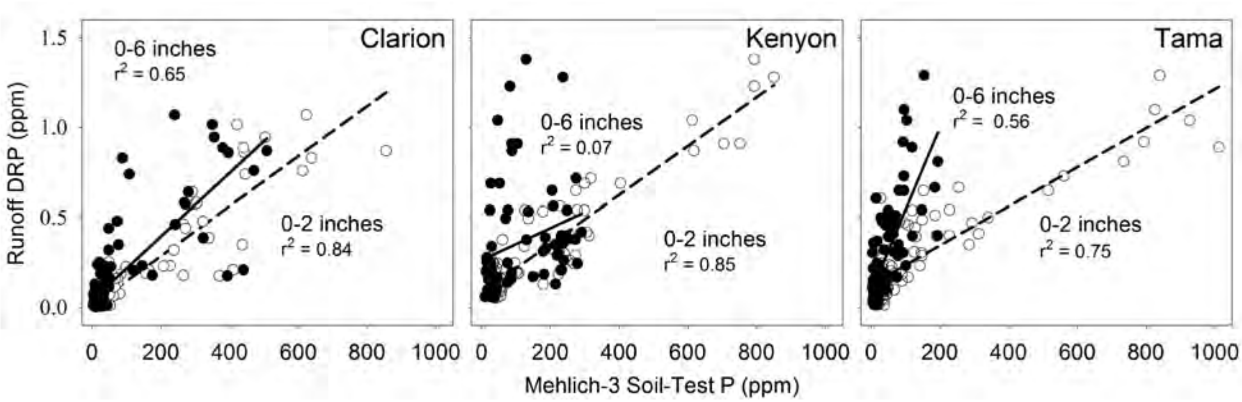

Figure 5. Relationship between dissolved reactive P (DRP) in runoff and soil-test P at two depths for Iowa soils with corn or soybean rotations and tillage or no-tillage (Allen and Mallarino, 2006).

Iowa research during the last two decades has shown that incorporation into the soil or subsurface banding and injection of fertilizer or manure P does not improve crop yield compared with broadcast application (as was shown by the example in Fig. 4). However, incorporation of the P into the soil without significantly increasing soil erosion reduces P concentration at or near the soil surface and reduces runoff P loss. The P loss with runoff from a surface application can be greatly reduced when the runoff event occurs after a few days or weeks after the application, however. This is shown by data in Figure 6. This figure shows that incorporation of P into the soil (swine manure incorporated by disking in this case) greatly reduced the P loss with runoff for runoff events occurring shortly after applications. But even with a few days delay in the occurrence of the runoff event, the effect of incorporation is much less, 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. These results are important because no-till has many advantages, and consideration of the probability of runoff events for the timing of P application could significantly reduce potential P loss due to a lack of P incorporation.

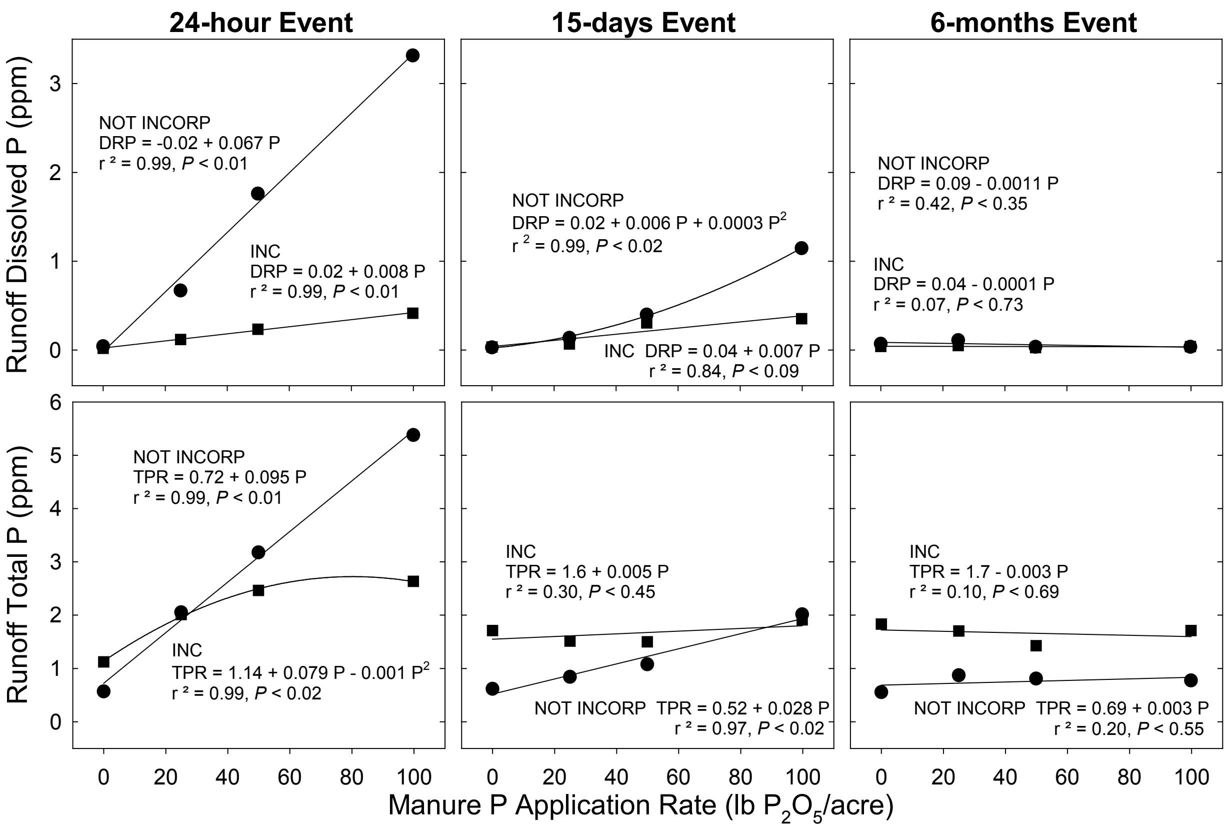

Figure 6. Effect of P application rate, incorporation, and time of rainfall on runoff P concentrations for an Iowa field. INC, swine manure incorporated; NO INCORP, swine manure not incorporated. Adapted from Allen and Mallarino (2008).

Sources of P and risk of P with surface runoff

Iowa research has shown that the availability of P in swine and poultry manure is 90 to 100% of that in inorganic fertilizers (Sawyer and Mallarino, 2008, Extension publication PMR 1003). Publication PMR 1003 provides a very wide P availability value for beef and dairy manures (60 to 100%) reflecting a lack of information from Iowa and highly variable values from other states. However, ongoing lab and field research in Iowa suggest that it is closer to that for swine and poultry manure. The risk of P loss from runoff events shortly after an application to the soil surface is higher for fertilizer than for animal manures when the total amount of P applied is the same. Data in Fig.

7 based on simulated rainfall from experiments in 21 Iowa fields shows that the P concentration in runoff for events occurring within 24 hours of surface application was the highest for fertilizer, intermediate for liquid swine manure, lowest for poultry and beef manure. Another significant result from this study was that the proportion of dissolved P in the runoff was about 50% or less for the manure but about 75% for the fertilizer. Both results can be explained by the higher proportion of P soluble in water in fertilizers (more than 95%) than in the manures (although highly variable). Therefore, when P is applied without injection or incorporation into the soil in periods of high probability of high intensity of rainfall, such as in early spring, the risk of total and dissolved P loss is much higher for fertilizer than for manure.

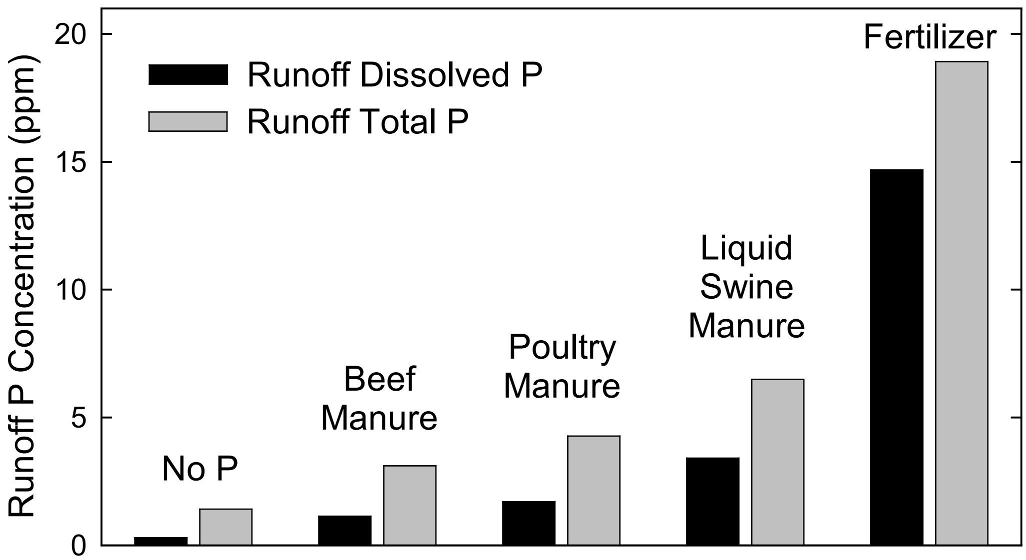

Figure 7. Runoff P for rainfall events within 24 hours of broadcast surface application of 100 lb P2O5/acre using several P sources. Averages of 21 Iowa sites (Haq and Mallarino, ISU).

Another period of the year where P loss with surface runoff can be elevated is in late winter, when snowmelt runoff or rainfall on partially frozen soil may occur. Iowa research shows that even with applications to frozen or snow-covered ground, the runoff P loss during this period often is lower compared with potential losses in runoff events shortly after application to the soil surface. However, losses can be large and there are striking differences between sources. This is shown by Fig. 8, which summarizes two years of research with application of fertilizer, liquid swine manure, and poultry manure in late fall or during winter. The concentration of dissolved and total P in snowmelt runoff were lower than in Fig. 7, and were higher for fertilizer, intermediate for liquid swine manure, and lowest for poultry manure.

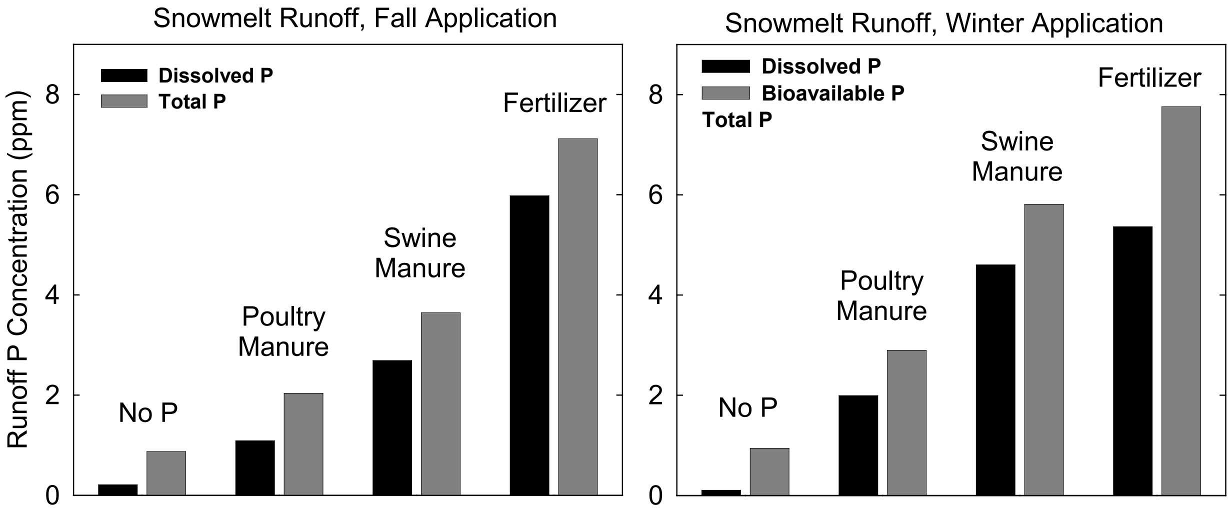

Figure 8. Phosphorus in snowmelt runoff after application of 100 lb P_2O_5/acre in the fall or to snow-covered ground using several P sources (Haq and Mallarino, ISU).

The Iowa Phosphorus Index is a useful tool to assess risk of P loss form fields

Agronomic and economic considerations do not justify fertilizer P application to high-testing soils. 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. The Iowa 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. 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). 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). Therefore, the Iowa P index can be used to identify nutrient, soil, and water management practices that can reduce high P loss and water quality impairment.

Summary: Do's and don'ts for optimizing yield and minimizing P water quality impacts

1. Use soil testing and crop removal to decide P fertilization rates:
    - Fertilization of low-testing soils is essential to increase crop yield and the profitability of crop production, and results in little increase in the risk of P loss from fields.
    - Maintaining soil-test P values in the optimum interpretation class eliminates the risk of yield loss, results in profitable and sustainable long-term crop production, and has acceptable impacts on water quality.
    - Applying P fertilizer to high-testing soils does not increase yield and reduce the profitability of crop production but increases the risk of P loss from fields and water quality impairment.
2. Use appropriate application time and methods:
    - Subsurface banding or injection of P does not increase yield but greatly reduces the risk of P loss with surface runoff. Incorporation of P into the soil with tillage also reduces P loss with surface runoff when the

tillage operation does not result in much increased soil erosion.

- Avoid application of P fertilizer without injection, subsurface banding, or incorporation into the soils during periods of high intensity and probability of rainfall, such in spring.
- Avoid applying P fertilizer and liquid swine manure to frozen or snow-covered and sloping ground. In these conditions, early spring P loss from application is highest for inorganic fertilizer, intermediate for liquid manure, and lowest for solid manure.

3. Manure is an excellent source of nutrients, but sometimes applying N-based manure results in too much soil P buildup over time. This is mainly the case when applying any manure type to continuous corn or N-based poultry manure to corn of corn-soybean rotations. In these cases, use of the Iowa P Index is very useful (and sometimes required by state and general agencies) to assess what nutrient, soil, and water management practices can be used to minimize the impact of increased soil P on P loss from fields.

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