IMPROVING PHOSPHORUS USE EFFICIENCY: RIGHT RATE, TIMING, AND PLACEMENT AND ENHANCED EFFICIENCY FERTILIZER SOURCES: RESEARCH SUMMARY

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ABSTRACT

Phosphorus (P) fertilization is essential for societal sustainability. However, plant P uptake is inefficient due to poor soil P solubility, especially for crops such as potato (*Solanum tuberosum* L.) plant due to relatively poor rooting efficiency and high demand. Phosphorus use efficiency (PUE) improves with the right rate, timing, placement, and with using enhanced efficiency fertilizer products (EEF). We have conducted several dozen studies over nearly two decades showing PUE is improved approximately two-three fold when using optimal rates, timings, and placements. But how do these efficiencies work in concert with each other and with EEF products? Our findings show that various technologies and management systems must account for the interactions between source, rate, timing, and placement. For example, research on two EEF products showed that they were no better than traditional P sources at standard rates. However, reducing the P rate by approximately 50% resulted in yield and crop quality increases of 5-8% in comparison to the traditional fertilizer applied at the same rate. In another example, failing to account for high residual soil test phosphorus levels resulted in poor PUE and even reductions in yields when EEF products were used in these conditions. Alone or in combination, these techniques offer an opportunity to increase PUE. A review of our findings shows yields increased an average of 6.2% when EEF were used at the correct rate, timing, and placement.

The fertilizer industry has recently promoted the concept of the 4R's of the correct or "right" source, rate, placement, and timing (http://www.nutrientstewardship.com/4rs). There are several important considerations when managing these with regard to phosphorus (P) fertilizer—which is reviewed by Hopkins (2015; note that much of the information found below is cited in that document and is not cited here due to space limitations) and some of our work on these is summarized below. Of particular importance is the concept that these considerations are not mutually exclusive—in other words, they impact each other. A primary focus of our work shows rate, timing, and placement need to be considered when selecting various Enhanced Efficiency Fertilizer (EEF) sources as discussed below.

PHOSPHORUS SOURCES

Effectiveness of the P fertilizer source is paramount. The P fertilizer needs to be water soluble or, at least, should have an eventual slow or control-release rate that is predictable and matched to plant need. Unless a slow or controlled-release pattern is desirable, P fertilizer should be at least 60% water soluble. Slow or controlled-release materials need to be similarly water soluble within the timeframe of a growing season. Most traditional sources, such as monoammonium phosphate (MAP; 11-52-0) and diammonium phosphate (DAP; 18-46-0), are greater than 90% soluble. Of course, liquid sources, such as ammonium polyphosphate (APP; 10-34-0 or 11-37-0) are already in solution. If compared fertilizers have similar solubility, the choice of which source to use becomes one of price, availability, convenience of application, and accompanying nutrients. Differences do exist across sources, but, in general, equal rates of soluble P result in approximately the same plant response regardless of sources used (as long as accompanying cations are not a factor).

The three fertilizers listed above make up the majority of P fertilizers manufactured and sold globally. However, there is an inherent problem with each in that much of the soluble P applied forms precipitates in the soil—with plants depending on re-solubilization in order to have access. As such, there are many additives for these sources, as well as other sources engineered as EEF's.

Phosphorus bound to the organic acids found in manure, compost, biosolids, or other waste materials increases P solubility and plant uptake dramatically. This effect can last for decades—as observed commonly in soils with a history of heavy manure/biosolid applications. There have been many efforts to harness the increase in P solubility when applied in combination with organic acids, but without having to apply the massive quantities of manures or other biosolids. This effect is accomplished potentially by adding concentrated humic, fulvic, or other organic acid additives directly with P fertilizers. This practice might improve PUE through a prolonged increase in P solubility. Doing so theoretically promotes bioavailability of P without the drawbacks, in some cases, of applications of manure and similar biosolids. However, the sale of humic substances, unlike fertilizer sales, is largely unregulated, and products may not be reliable. Thus, buyers should work with products that are from reliable companies who can provide independent research confirmation. Plants might not benefit from additional application of organic substances in many soils that are naturally high in humic substances.

Plants deficient in P upregulate root exudation of organic acids into the soil, and various organic acids mobilize poorly soluble mineral nutrients with citrate, malate and oxalate the most common and effective at mobilizing P. Their ability to reduce P precipitation and improve solubility of poorly soluble phosphates is potentially valuable in meeting plant P demands.

In the case of potato grown in calcareous soil, Hopkins (2015) reported that humic acid use increased plant P uptake, resulting in increased tuber quality and yield. More recent developments with organic acids combined with P fertilizer have been reported with a unique P fertilizer, Carbond P® (Land View Inc., Rupert, Idaho, USA). The P in this product is bonded chemically with organic acids, which is in contrast to the simple mixing of P fertilizer with an organic acid product prior to application. This work is focused on low-OM soils, but similar results were found for moderate OM soil with an apparent diminished effect when soil OM is high. The effect of Carbond P is not likely due to plant physiological impacts, but rather more likely related to impacts of the organic acids on soil P chemistry.

Another EEF source is AVAIL® (Specialty Fertilizer Products, Leawood, Kansas). Hopkins (2015) reviews the proposed mode of action for AVAIL, a high charge density polymer that sequesters interfering cations. He also reviews the work performed on AVAIL and its impact on P soil chemistry. Positive responses were observed and published for rice and two potato studies with mixed responses. Hopkins (2015) reviews other informally reported studies on a variety of crops. In some cases, yield increases have been reported, while in others yields were not impacted or results were mixed. One conclusion from this review was that many of the non-responsive reports occurred on soils with medium to high soil test P where probability of P response would be unlikely. AVAIL was effective only when the rate of P was reduced. In other words, if a plant already has adequate P due to high rates of P fertilizer or residual P in the soil, AVAIL or any other P fertilizer enhancement will not likely provide any benefit.

PHOSPHORUS RATE

Choosing the right rate can be a difficult proposition. Thousands of rate studies conducted on many crops grown in a variety of soils show the optimum rate is only somewhat predictable. Many parameters are integrated by the plant-soil system which affect the optimum rate.

In addition to residual soil P, yield potential is another important factor that impacts rate. Some soil and environmental conditions drastically limit yields. Assuming that this yield limitation is not related to P uptake, such as poor availability of other nutrients or root/vascular system diseases, it is likely that the optimum P rate is relatively low. Evaluation of the soil system and the history of the field, including yield history, can be used to help predict rate adjustments. It is common for P recommendations to provide a base P recommendation with an adjustment upward in rate of fertilizer for each increment in yield potential.

Environmental conditions and many pest-related impacts on yield cannot be predicted easily. In the case of N, in-season adjustments can easily be made to cut back or add to the forecasted amount needed for the whole season. This adjustment is not as efficiently done for P due to lack of mobility previously discussed. However, Hopkins (2015) found that, for potato, an in-season adjustment could be made by fertigating P through the irrigation system if petiole tissue sampling indicates a need. Of course, a similar approach could be done by applying dry fertilizer via airplane or field spreader for non-irrigated fields, but the cost and efficiency of uptake are problematic. Furthermore, preplant-applied fertilizer obviously cannot be picked back up in situations where the yields are being limited due to some unforeseen problem. Although potato is somewhat efficient for in-season fertilizer use due to a prolific amount of surface-feeding roots once the canopy closes, other crops are not as efficient. Alfalfa seems to be responsive to P fertilization on an established crop, but corn is not as efficient in its in-season uptake. Every effort should be employed to apply the correct rate of fertilizer P to plants preplant and incorporated into the soil based on soil test. Additional in-season applications should be applied if tissue analysis indicates a need and if the crop has been shown to be responsive. However, it is common that the costs for these in-season applications are higher than soil-incorporated applications and the uptake efficiency is less.

Although soil testing is a valuable tool, it is not a perfect predictor of P fertilizer need. This is particularly problematic with potato and other inefficient P responders. Some researchers have found soil testing to be correlated highly to plant response, but in other studies the results were less conclusive with tuber yield and quality responses at high soil test levels. Regardless, potato responds to fertilizer P at soil test levels higher than what is sufficient for most agronomic crops.

Hopkins (2015) provided a review of the confounding information available for P rates—stating that economical P rates for potato are clearly well above those required for most other crops. Long-term studies with corn and soybean in Iowa and Minnesota showed that applying P at crop removal rates when soil test P were in the medium range (16 to 20 ppm Bray P1) achieved maximum economic yields. These rates are 2-6 times less than those required by potato and other P-inefficient crops. Most other agronomic crops are similar to corn and soybean—with typical rates near removal amounts when soil test levels are moderate.

PHOSPHORUS TIMING AND PLACEMENT

Several timing and placement choices exist, including preplant broadcast either left on the surface (no or minimum tillage systems) or incorporated into soil, concentrated bands applied with or near the seed, concentrated bands applied either during the season to the surface or injected between rows, in-season broadcast or injected into irrigation water, and small liquid volume foliar sprays. Each of these has pros and cons discussed below.

With N fertilization, it is a good management practice to apply P in-season through slow- or controlled release sources, with irrigation water, or as foliar or dry broadcast soil applications. Loss mechanisms for N result in leaching of NO_3^- and gaseous losses of NH_3 and nitrous oxide (N_2O) via volatilization and denitrification. However, the chemistry of P is very different from N, having none of these loss mechanisms. This principle is not well understood and, as such, is common lore for growers to assume that the same constraints that hold for N will also hold for P.

There is a common thought process that the cascading loss of P solubility over time is a reason to encourage in-season applications of P or recommend application directly to leaves to avoid soil interactions. Although these seem logical, they are flawed in practice due to the lack of mobility of P through soil and the inefficiency of foliar applications. Although the loss of P solubility with time is a real effect, the reality is that there is little difference when comparing availability from a preplant vs. an in-season application a few weeks later. Even when comparing a fall vs. spring application, the difference in P availability is not tremendous. For instance, no significant difference between fall and spring-applied P fertilizer for 'Russet Burbank' potato was reported by Hopkins (2015). In the case of lettuce, waiting to apply P in-season resulted in crop losses compared to applying ample P preplant and without interruptions in supply. Similar findings were made for muskmelon and sugarbeet. The timing of P application is not a critical issue in P management, as long as adequate P is available through the season, as P in soil solution tends to self-regulate based on equilibrium chemistry.

As discussed previously, an in-season application of P is inherently inefficient because, unlike N and many other nutrients, P is not mobile in the soil, and therefore applied P may remain in the surface layer where it is poorly available to plant roots. Broadcast and fertigated in-season applications may result in P deposition in the top few mm of soil where root biomass may be low and/or soil is often dry. High concentration of P in surface soil is also an environmental concern because the primary P loss mechanism from soil is erosional transport into surface water, and the nearer to the surface that P is "fixed" the greater the chance of erosion. The surface deposition problem possibly could be overcome with in-season P applications applied as a band knifed into the soil, but the damage from root pruning could offset the benefit of applying P fertilizer to growing plants as compared to a preplant fertilization if the knife application enters the root zone.

Despite the fact that in-season application of P is less efficient than incorporating P into the soil prior to or soon after planting, this practice is not completely ineffective and is sometimes necessary. In-season application of P is generally as effective as pre-season application if incorporated into the soil and root pruning are not significant, but this can be difficult to achieve.

However, in-season P applications that do not include placement into the soil are relatively inefficient. It makes theoretical sense to apply all of the anticipated P fertilizer required prior to planting in the rooting zone since timing is not a major factor. Although some species, especially perennials, such as alfalfa and grasses, are adept at P uptake through roots close to the soil surface, many other species are very poor at P uptake from surface soil when P fertilizer applications concentrate it in this zone. In the case of potato, it has been shown that midseason P applications can be effective—likely due to an upright canopy architecture (high percentage of water with dissolved solutes, such as P, follow the stems to be deposited at the base of the plant) and an abundance of surface-feeding roots after the canopy closes and completely covers the soil. However, these in-season P applications are not as effective as when preplant P is mixed in the soil and in better contact with plant roots.

The rate of P fertilization was found to be 50% for banded vs. broadcast applications to vegetable crops. The efficiency of banding vs. broadcast is much greater at low vs. high soil test values with about a threefold increase at low soil P, but approaching equivalent status at high. Similar findings were made for corn, winter wheat, and other agronomic crops.

In-season P application should probably be viewed as a means of last resort or rescue, and used only when tissue analysis indicates a P deficiency. In-season applications should only be supplementary to soil-incorporated P applications, and only if tissue analysis shows a need. Hopkins (2015) states that preplant P fertilization resulted in significant improvements in yield. Although there were trends for yield increase, the in-season and the split (50% preplant and 50% in-season) applications did not result in significant increases over the unfertilized control. Further work showed that, although incorporation into the soil is the best option, "rescue" in-season P application have some merit with potato when P was under applied prior to planting.

Hopkins (2015) reports that in-season P application gave a slight, consistent US No. 1 yield increase at all preplant P levels in the study (0, 100, 200, and 300 lb P_2O_5 ac^{-1}). The response to preplant P increased steadily with rate increase, but the in-season application resulted in further increases in yield, even at the highest P rate evaluated. A similar response occurred for total yield, although the response to preplant P leveled off at the first rate of applied P. Phosphorus uptake and yields generally increase with supplemental P fertigation, although the results can be mixed.

Nutrient placement can increase PUE. Fertilization can impact P availability through at least two avenues. First, there are more microsites with readily soluble adsorbed or precipitated P. Each site increases the likelihood of a root encounter and uptake. Broadcast fertilization greatly impacts this means of P supply to plants. The other avenue is through an increase in soil solution equilibrium P level. A concentrated fertilizer band or point injection greatly amplifies these effects in a small zone in the soil, providing a highly soluble pool of P for plant uptake. There is about a 60-fold increase in the bioavailable P in the center of a fertilizer band compared to when the same amount is broadcast in the bulk soil. This increase is temporary, but allows plant roots to "bathe" in soluble P, particularly during the critical early-season growth period. PUE will likely increase if P banding contacts about 5% of the soil volume, especially with high P fixing soils low in soil test P.

For maximum effect, the fertilizer needs to be placed in an area where roots are likely to be congregated. For corn and most other species, placement of a concentrated band is generally recommended at 2 in. to the side and 2 in. down from the seed for interception by early roots which tend to grow diagonally. Potato is similar, although placement is generally slightly further away at 3 in. with a wider range of acceptable depth ranging from 3 in. above or below the seed piece. Placement too far from the main root system results in little or no P uptake, especially for species with small roots systems. There is virtually no P uptake from labeled fertilizer applied in the adjacent furrow or beyond for potato. And, there is little P uptake for banded fertilizer applied below 1 foot and the most efficient uptake occurs 2 in. to the side of the seed piece. For sugarbeet, placement should be directly below the seed in order to intercept the dominant taproot in the first few weeks of growth.

It is important to understand root morphology and architecture of individual species in order to most effectively apply a concentrated fertilizer band. Usually these concentrated fertilizer bands are applied at planting. However, in some cases, the application is applied preplant. This is especially common for potato, with the P often applied when rows are formed. In this case, it is essential that the concentrated band be placed to the side of the seed piece and deeper than the planting depth to avoid disruption of the band at planting when the soil is disturbed. It is crucial that the concentrated band of P remains intact in order to realize the benefit of increased P solubility.

Appropriately placed fertilizer bands increase P uptake efficiency 25%-35% (first year recovery) compared with 1%-10% when the P is broadcast applied. Radioactively labeled P resulted in a doubling of P recovery from a concentrated band (2 in. to the side and 1 in. down from the seed) compared to a broadcast application. Although not always a replacement for broadcast fertilizer P, adding P to soil in a concentrated band often results in additional increases in potato tuber yield and quality over a single broadcast application. Banding P increases P uptake, especially for early-season growth when P availability is most limiting due to low soil temperatures and a poorly developed root system. These concentrated bands often result in increased rates of early-season shoot and root growth and higher concentrations of potato petiole P, with the consequence being gains in yield and quality. However, early-season growth boosts due to concentrated bands do not always equate to end of season yield increases, as plants can sometimes "catch-up" if the conditions and length of growing season are optimum.

Recently reported research results show an additive response when banded fertilizer P was applied in conjunction with broadcast-incorporated P for potato grown in calcareous soil (2%-12% $CaCO_3$) with Olsen bicarbonate extractable P of 8-18 ppm. In moderately high testing soils, such as those that have received heavy manure applications over time, plants may respond to a band application even when the soil test recommends no additional P applications. The effectiveness of banded P for potato has been shown to vary with P source in calcareous soil, with the pH of the fertilizer solution being a key factor. Banding has also been shown to be beneficial in lower pH soils by concentrating P near the early developing root system.

Despite the benefits of applying P in a concentrated band, all plant roots require adequate P throughout the entire rooting zone. Although P is mobile in plants, it may not be translocated efficiently from one distant root to another. This is because the P would have to be transported to the shoots and then back to the root with photosynthates; consequently, it is best to apply both broadcast and banded P to soils with low to medium soil test levels. When soil test values are high, it is generally not recommended to apply a broadcast P. However, there are reported incidents of responses to banded P in soils with high residual P. It is essential that all of the P be banded on soils with a high potential for P fixation.

It should be noted, however, that too much of a good thing can be bad. Negative results have been observed when banded P was applied in direct contact with potato seed pieces. Other species show toxicity if high rates are applied in direct contact with seeds. Plants need salts in order to regulate water uptake, and all nutrients are found in salt form. However, excessive salts desiccate plant tissues if the soil osmotic potential becomes extremely negative, particularly for germinating seeds and seedlings. Fertilizer can be applied in direct seed contact as long as the rate is not too high. Orthophosphate is a salt component, but when it is applied as a fertilizer its salt effect is minimal because the majority is quickly precipitated into solid forms. As such, its direct impact on salt concentration is less than more soluble nutrients, such as N and K. Thus, P can be directly applied to seed more safely relative to other nutrients, although accompanying cations are often soluble salts. To be safe, no fertilizer should be applied in direct seed contact without research showing that the rate applied is acceptable for the species under the specified soil and environmental conditions. Note that because salt damage is a function of soil moisture status, dry soil conditions are relatively more likely to result in salt damage to plants. Furthermore, small seeded species tend to be more readily impacted by salts in close proximity to the seed or seedling than species with large seeds.

REVIEW OF EEF PHOSPHORUS STUDIES

We have conducted several dozen P source studies using various EEF fertilizers over a period of 17 years. In addition, we have evaluated over 500 studies of other researchers. Combining these studies shows clear trends. First, using a product with enhanced efficiency does not generally result in yields greater than traditional products when the latter is applied at its optimum rate. In other words, adequate P nutrition can be achieved with traditional fertilizers and adding more does not increase yields—a basic but often forgotten tenet of soil fertility. Table 1 shows the results of a meta-analysis for crop yield/quality for 289 studies with EEF products on a wide variety of crops (potato, corn, sugarbeet, small grains, alfalfa, etc.). In order to make a valid comparison, we only included studies in the analysis where a half rate of P for the EEF was one of the treatments. In each case, the EEF product was applied at a full (100% Rate) and a half (50% Rate) of P fertilizer and compared to the same rates of a traditional fertilizer (MAP, DAP, or APP). Other data (rates, placements, etc.) were often also available, but we have omitted here for simplification. These results show the primary value of the EEF fertilizers is that a lower rate of P can be used to achieve the same result as a high rate of traditional fertilizer. The two most commonly studied products in our analysis were AVAIL and Carbond P—making up 151 and 98 of the studies, respectively. Several “other” EEF products were evaluated but there were not enough of any one of these to do its own evaluation and, thus, they were lumped together. (We note that the 50% rate is somewhat arbitrary and included because this was the most common rate in a majority of these studies. The actual optimum rate for each source and circumstance may be higher or lower than 50%—as determined through further study.

Table 1. Meta-analysis of relative crop yield/quality increases for 289 studies with phosphorus Enhanced Efficiency Fertilizers (EEF) products. In each case, the EEF product was applied at a full (100% Rate) and a half (50% Rate) of P fertilizer and compared to the same rates of a traditional fertilizer (MAP, DAP, or APP). Statistical significance ($P < 0.05$) of the EEF compared to the traditional fertilizer treatment is indicated by **bold-faced** type.

EEF Source	50% Rate	100% Rate
AVAIL	**5.3%**	0.9%
Carbond P	**7.9%**	2.1%
Other	**4.6%**	0.2%

When averaged across all studies, the net crop yield/quality increase was a significant 6.3%

increase. It is important to note that only studies where the soil test P was indicative that a fertilizer response was likely were included in this analysis. Many studies not included in these results were done by other researchers under conditions where the soil test P was high or very high and, not surprisingly, the response at these sites was not generally significant for P with or without EEF technology.

Placement and timing were also important for these studies. For example, the Hopkins studies on both AVAIL and Carbond P clearly showed better responses when the P was applied in a concentrated band in close proximity to early forming roots as compared to broadcast, fertigation, or foliar applications. The PUE of 77 studies where this was measured is shown in Table 2.

Table 2. Relative increase in Phosphorus Use Efficiency (PUE) for studies with P applied as: broadcast-not incorporated (2 alfalfa and 14 turfgrass studies), broadcast-incorporated (10 potato and 5 corn studies), concentrated band applied in direct pathway of early season roots (25 potato, 8 corn, and 5 sugarbeet studies), fertigation (2 potato and 1 corn studies), and foliar (5 potato studies). PUE was measured by yield/crop increase per unit of fertilizer P applied—comparing various Enhanced Efficiency Fertilizers (EEF) to traditional P fertilizers. In each case, the EEF product was applied at a full (100% Rate) and a half (50% Rate) of P fertilizer and compared to the same rates of a traditional fertilizer (MAP, DAP, or APP). Statistical significance ($P < 0.05$) of the EEF compared to the traditional fertilizer treatment is indicated by **bold-faced** type.

Method of Application	50% Rate	100% Rate
Broadcast-Not Incorporated	**8.1%**	1.2%
Broadcast-Incorporated	**4.9%**	2.1%
Concentrated Band	**10.4%**	5.4%
Fertigation	6.1%	5.8%
Foliar	**8.5%**	**7.8%**

It is very apparent that source, rate, timing, and placement are all important considerations, and each need to be factored in when improvements are made to any one of these parameters. In particular, the use of EEF products necessitates a reduction in P rate; and timing and placement may impact the level of efficiency gained by an EEF product.

REFERENCE

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