FUTURE DIRECTIONS FOR AGRICULTURAL PHOSPHORUS RESEARCH

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Edited by F. J. Sikora

Agricultural Research Department
National Fertilizer and Environmental Research Center
Tennessee Valley Authority

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Management for Residual Fertilizer Phosphorus in Soils

Ardell D. Halvorson

ABSTRACT

This paper reviews the effects of residual fertilizer P on crop yields, soil test levels, P fertilizer use efficiency, and economics of P fertilization. Crop yields in a long-term P study were responding positively to residual P fertilizer 15 years after an initial one-time P application of 45, 90, or 160 kg P ha^{-1}. Soil test P levels in this study appeared to establish a new, higher soil test P equilibrium level about 12 years after a one-time P application of 45, 90, and 160 kg P ha^{-1}. Phosphorus fertilizer use efficiency improved with each additional year of crop production. Economic returns from single P applications to soils deficient in P have been shown to increase with time. Cumulative profits from a single P application varied with initial P rate, but long-term profits tended to be greater for the higher rates (>80 kg P ha^{-1}).

Soil P deficiency for cereal grains and other crops is common in the Great Plains (PPI Staff, 1985, 1987). Fertilizer P management varies with location and site specific conditions, such as initial soil test P level, soil type, soil pH, available application equipment, crop rotation, and tillage system. Soil testing is the best tool available to assess the need for P fertilization. Accurately assessing soil P availability status and the quantity of P fertilizer required to alleviate P deficiency is necessary if maximum economic yields (MEY) are to be obtained.

The current emphasis on the need for higher P application rates to optimize grain yield potentials necessitates that the short- and long-term economic and environmental impacts of P fertilizer management be evaluated. Method and rate of P application can affect the level of grain yield response of wheat. If low rates (< 15 kg P ha^{-1}) of fertilizer P are to be applied to soils testing "low" in plant-available P, then banding the fertilizer P below or with the seed is generally more efficient and results in greater yield increases than broadcast P during the first year of application (Peterson et al., 1981; Sleight et al., 1984; Westfall et al., 1986). However, if sufficient fertilizer P is to be added to attain optimum wheat yields on a soil testing "low" in P, then method of placement may not be as critical. On soils testing "medium" to "high" in plant-available P, the difference in effectiveness between broadcast and band applications is lessened (Peterson et al., 1981; Halvorson et al., 1987; A.D. Halvorson and J.L. Havlin, unpublished data). The recent work of Wagar et al. (1986) supports this hypothesis. They found that the five-year cumulative grain yield from a single, broadcast P application of 80 kg P ha^{-1} was greater than from 20 kg P ha^{-1} applied each of 5 crop years with the seed. Thus the broadcast treatment produced at or near optimum yields each year, whereas the seed-placed P treatment produced at less than optimum yield potential for the first several crops. Wagar et al. (1986) also found that near maximum wheat yields were produced from the residual of a one-time application of 40 kg P ha^{-1} broadcast plus 10 kg P ha^{-1} applied with the seed each crop year. The latter treatment would be desirable from the standpoint of extending the P fertilizer costs over a longer time frame and still being able to maintain near optimum yield potential.

Most P soil-fertility research in the Great Plains has been limited to evaluating wheat response to P fertilizer application from a one crop harvest (Dahnke et al., 1986; Fiedler et al., 1987; Follett et al., 1987; Leikam et al., 1983; Peterson et al., 1981; Westfall et al., 1986). Effects of residual P fertilization in the northern Great Plains have been positive in increasing small grain yields (Bailey et al., 1977; Black, 1982; Halvorson and Black, 1985a; Read et al., 1977; Roberts and Stewart, 1987; Wager et al., 1986) as well as economic benefits in increasing farm profit potential (Halvorson et al., 1986; Jose, 1981; Roberts and Stewart, 1987). Many of these studies were conducted with conventional dryland tillage systems and a crop-fallow cropping sequence. On a long-term (4 crop years) basis, a single broadcast application of P fertilizer (80 kg P ha^{-1}) may be equally as effective in increasing wheat yields as an equal quantity of P fertilizer applied in annual increments (20 kg P ha^{-1}) as a band application (Roberts and Stewart, 1987; Sleight et al., 1984). Long-term P studies conducted by Alessi and Power (1980), Bailey et al. (1977), Black (1982), Halvorson and Black (1985a and 1985b), and Read et al. (1977) in the northern Great Plains indicate that benefits from a single P fertilizer application at rates of 45 kg P ha^{-1} or more may last as long as 16 years, depending on initial rate of application and cropping history. Halvorson (1989) reported that irrigated winter wheat, grown annually on the same land, responded positively to residual broadcast fertilizer P (34 and 67 kg ha^{-1}) under no-till conditions at Akron, Colorado.

Multiple year responses of alfalfa and grain sorghum to single applications of P fertilizer have been investigated in the central Great Plains (Havlin et al., 1984; Janssen et al., 1985, Schlegel et al., 1986). The effects of P fertilization on changing soil test P levels of several central Great Plains soils for several years was shown by Hooker et al. (1980); however, wheat yields were not reported. Halvorson and

United States Dept. of Agriculture-Agricultural Research Service. Box 400, Akron, Colorado 80720 (telephone, 303-345-2259).

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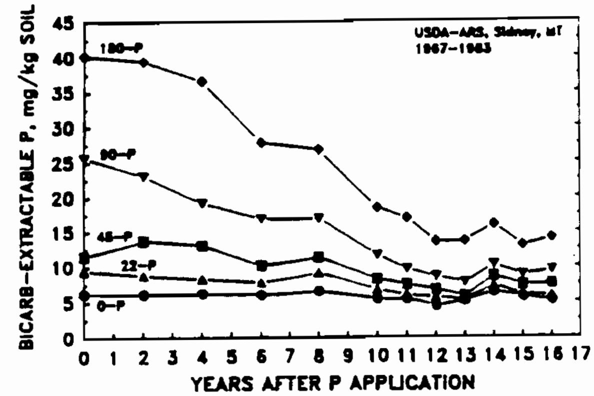

Fig. 1 Changes in soil test P levels with time after an initial, one-time application of P fertilizer to a loam soil.

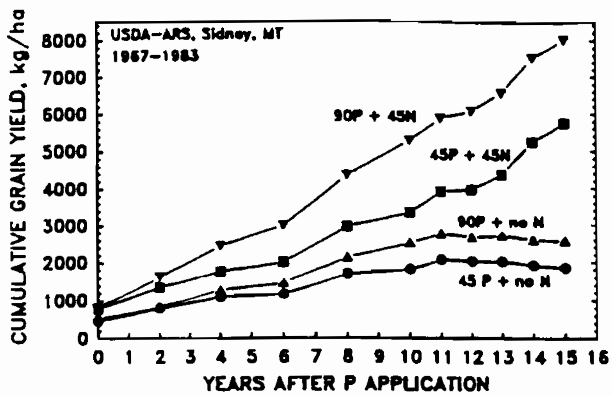

Fig. 2. Cumulative grain with years after initial P application with or without 45 kg N ha^{-1} each crop year.

Black (1985a) suggested that a one-time, high-rate (50 kg P ha^{-1}) application of P fertilizer may be one way to satisfy the P needs of crops grown with reduced and no-till systems for several years. A study currently being conducted by A. D. Halvorson and J. L. Havlin is evaluating this suggestion and is also comparing the effects of P placement method on the long-term (4 crop years) effectiveness of residual P fertilizer.

The objectives of this paper are to: 1) demonstrate crop response to residual P fertilizer; 2) show improved P fertilizer use efficiency with time; 3) show need to have adequate N to get efficient P use; 4) demonstrate long-term profit potential from high rates of P fertilization; and 5) discuss potential research needs regarding residual P in soils. Results from some of the residual P fertilizer research conducted in the Great Plains will be the primary source of information.

MATERIALS AND METHODS

Since the results reported are primarily from published information, details of methods and materials used will not be presented herein. The reader is referred to the literature citation for more detail. The long-term residual P placement x rate studies that A. D. Halvorson and J. L. Havlin are conducting will be briefly described. Two sites are being examined, one near Peetz, Colorado, and one near Morrill, Nebraska, both on calcareous loam soils. The initial $NaHCO_3$-extractable soil P level (0 -15 cm depth) was 10 mg P kg^{-1} soil, a "medium" soil test P level, at the Peetz site and 4 mg P kg^{-1} soil, "low" level, at the Morrill site. Fertilizer P placement methods at Peetz are: a) broadcast prior to planting with no incorporation (BC W/O INC.); b) broadcast prior to planting with shallow incorporation (7.5 cm depth) using a disk (BC INC.); and c) banded below seed (BD) at planting with drill at about 7.5 cm below the soil surface (3.8 cm to the side and 3.8 cm below the seed). Fertilizer P rates were 0, 34, 67, 101, and 134 kg ha^{-1} were applied as triple superphosphate (TSP). At the Morrill site, the P placement methods are: a) broadcast incorporated prior to planting; b) banded below seed at planting with drill at about a 7.5 cm depth; and c) placed with the seed at planting at half the established P rate for two crop years. Fertilizer P rates are 0, 5.6, 11.2, 22.4, and 44.8 kg P/ha. Soil test P data represent samples from the 0 to 15 cm soil depth that were analyzed for $NaHCO_3$-extractable soil P (Olsen et al., 1954; Watanabe and Olsen, 1965).

RESULTS AND DISCUSSION

Halvorson and Black (1985a) showed that soil test P levels were increased above the initial soil test P level by the one-time P applications for more than 16 years on a Williams loam in Montana (Fig. 1). After the initial increase, soil test P levels declined for about 12 years and then stabilized at a higher soil test level than was initially present, thus establishing what appears to be a new equilibrium level of soil available P. Similar changes in soil test P levels with time were reported by Fixen (1986). Crop yields reported by Halvorson and Black (1985a) were also improved by the residual P fertilizer for a period of 16 years (Fig. 2). Based on soil test P levels for the highest P rates, grain yields would have been increased for several more cropping seasons had the study been continued.

The relationship between the $NaHCO_3$ P test and relative yield potential of wheat grown in a dryland wheat-fallow system is shown in Fig. 3 (Halvorson, 1986). These data indicate that a 26 mg kg^{-1} P level in the surface 15 cm of soil is needed to achieve 100% of the wheat yield potential in this semiarid environment. The type of relationship shown in Fig. 3 is useful in estimating potential yield reductions caused by inadequate available P levels. When P fertilizer is added to most soils in the Great Plains, an increase can be expected in soil test P levels. The amount of increase will depend upon soil texture and other soil characteristics. Halvorson and Kresge (1982) used this approach to estimate the amount of broadcast-incorporated P fertilizer needed to optimize yields. If less P fertilizer is applied than recommended, wheat yield potentials are reduced along with N fertilizer needs. Halvorson and Kresge (1982) estimated that 4 to 5 kg P ha^{-1} was needed to raise the soil test P level 1 mg kg^{-1}. Based on initial soil test P level and P application rate, Halvorson et

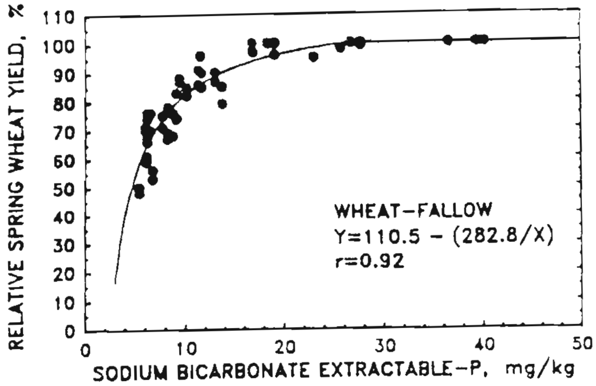

Fig. 3. Relative spring wheat yield as a function of soil test P.

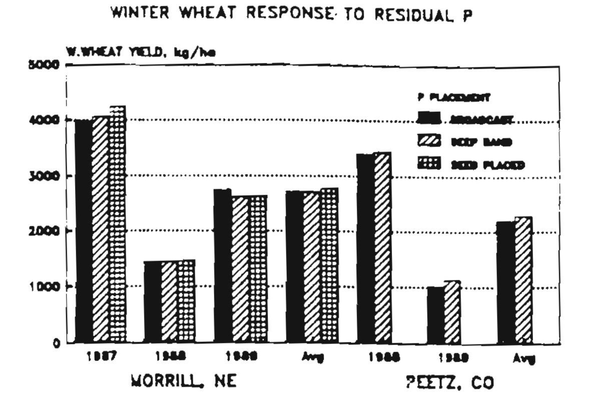

Fig. 4. Winter wheat yield response to residual fertilizer P as a function of P application method.

al. (1987) developed a computer routine to predict the change in soil test P level with time on a Williams loam after an application of P fertilizer in a wheat-fallow system. This approach could be used, along with P removal rate by the crop, to predict when future additions of P will be needed. Similar data are needed for other soil types and cropping conditions.

In general, fertilizer P rates should be applied to bring the soil test level to approximately 21 mg kg^{-1} on calcareous soils to maximize wheat yields and response to N fertilization. Halvorson and Black (1985a) found adequate levels of P were needed to obtain optimum response to N fertilization (Fig. 2). As more intensive wheat management systems are adopted, higher yield potentials may require higher soil test P levels (21 to 26 mg P kg^{-1}) to eliminate P deficiency.

Application of 0, 34, and 67 kg P ha^{-1} to a Weld silt loam at Akron, Colorado, in the fall of 1983 significantly increased the soil test P level described by the linear relationship: Soil Test P = 4.92 + 0.23 (kg P ha^{-1} added), r^2 = 0.98 in 1984 (Halvorson, 1989). Soil test P maintained significant linear relationships with initial P application rate in 1985 (Soil Test P = 3.46 + 0.146 (kg P ha^{-1} added), r^2 = 0.90) and in 1986 (Soil Test P = 2.63 + 0.092 (kg P ha^{-1} added); r^2 = 0.90). Soil test P levels, however, declined each year for each P rate. The decline in soil test P probably reflects conversion of applied fertilizer P to non-extractable forms in the soil and P removal by the wheat crop. One application of 34 and 67 kg P ha^{-1} significantly increased winter wheat grain yields each of three crop years. However, application of 67 kg P ha^{-1} may have caused a Zn deficiency in winter wheat at this location the first year of P application, resulting in lower yields than where 34 kg P ha^{-1} had been applied. Singh et al. (1986) also reported Zn deficiency in wheat following a high rate of P application.

Adequate levels of N are essential to get full benefit from residual P fertilizer and efficient P utilization, regardless of the method of P application. Halvorson and Havlin (unpublished data) found that the addition of 45 kg N ha^{-1} increased winter wheat response to one application of 45 kg P ha^{-1} at Morrill, Nebraska. They also found that initial P placement method had no effect on winter wheat response to residual P (Fig. 4). Yield data from Montana (Black, 1982; Halvorson and Black, 1985a) also show that N fertilization was needed to get optimum response of spring wheat to residual P fertilizer (Fig. 2). Thus, by having adequate P present and balancing the N needs of the crop based on yield potential, optimum yield and profit potentials can be realized.

Halvorson (1989) found that the presence of adequate levels of residual P also improved N use efficiency by irrigated winter wheat. Residual soil NO_3-N levels in the soil profile were significantly less where adequate P was present, reducing the potential for NO_3 contamination of groundwater. Phosphorus uptake and removal with the harvested grain generally increased as the soil NO_3-N plus fertilizer N level increased to an adequate level. Estimated fertilizer P recovery of the 34 kg P ha^{-1} rate in the harvested grain of three winter wheat crops was 9.7, 42.4, 26.8, 22.9, and 24.7% for the 0, 34, 67, 134, and 268 kg N ha^{-1} treatments, respectively. Estimated fertilizer P recovery of the 67 kg P ha^{-1} rate applied in 1983 in the harvested grain of three winter wheat crops was 7.2, 22.4, 27.6, 26.0, and 23.3% for the same respective N treatments. With no N added, cumulative P fertilizer recovery for the 34 kg P ha^{-1} rate increased with each additional year of cropping from 5.0 to 5.9 to 9.7% for 1984, 1985, and 1986, respectively, and with 67 kg N ha^{-1} added from 12.9 to 21.2 to 26.8% for the same respective years. For the 67 kg ha^{-1} P rate, cumulative P fertilizer recovery was 2.1, 4.9, and 7.3% without N and 7.6, 19.1, and 27.6% with 67 kg N ha^{-1} added for 1984, 1985, and 1986 respectively. Thus, time and N fertilization significantly improved the recovery of fertilizer P in the harvested grain. Similar increases in P recovery could be calculated from data presented by Halvorson and Black (1985b).

The positive benefits of residual P fertilizer availability on irrigated and dryland crop yields in the Great Plains demonstrate that P fertilizer-use efficiency needs to be evaluated over a longer period than just one crop year. It may need to be evaluated for more than 20 years, depending on P rate, soil type, and cropping system.

ECONOMICS

Many farmers today consider themselves economically stressed as a result of rising production costs while crop prices have tended to remain relatively constant, even when considering Federal price support programs. Current farm management emphasis is on increasing input-use efficiency. Adequate levels of plant nutrients are essential for obtaining optimum economic yields while protecting the environment. By soil testing, more accurate fertilizer recommendations can be made by giving credit for residual N and P in the soil profile, thus helping farmers achieve the required nutrient balance without over- or under-investing in fertilizer. This will require that soils previously receiving banded P fertilizer applications be properly sampled to insure that the soil test accurately reflects the true P status of the soil.

The short- (1-2 crop yr) and long-term (> 2 crop yr) economics of P fertilization need to be considered (Fig. 5). The long-term economics of a large one-time application of P fertilizer can be profitable on some soils (Jose, 1981; Halvorson et al., 1986; Wagar et al., 1986). However, the short-term profitability may be marginal for a one-time large P application (> 90 kg P ha^{-1}). Jose (1981) concluded there was a long-term economic advantage of a single high rate broadcast P application over an equal quantity of P band applied to several crops at a lower rate at dryland sites in Canada.

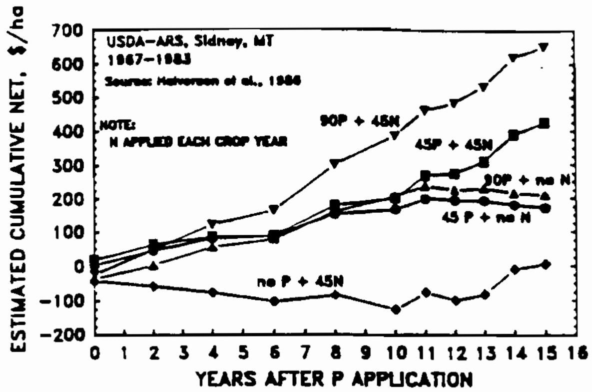

Fig. 5. Cumulative net return with time as a function of a single P application and 45 kg N ha-1 applied each crop year.

Crop price, fertilizer cost, and current soil test P level will govern how much P can be profitably applied in a given year. The investment in P fertilizer may need to be amortized over several years, similar to machinery, in order to maximize wheat yields and optimize responses to N fertilization. Application of adequate fertilizer P to bring the soil test P level to about 21 mg P kg^{-1} (Olsen P test) or about 30 mg P kg^{-1} (Bray-Kurtz P1) followed by smaller annual P applications (< 10 kg ha^{-1}) to maintain this soil test level may result in optimum wheat yields and optimum short- and long-term profitability. This approach to P fertilization would probably provide the potential for optimum wheat yields each crop year. In dry years, a high level of soil P (20 mg kg^{-1}) will increase yields and in the wet years, a high level of soil P will provide that opportunity to more efficiently utilize available water supplies, providing that N is not limiting. For example, Black (1982) showed that spring wheat yields were increased an average of 417 kg ha^{-1} in dry years while yields were increased by 712 kg ha^{-1} with 180 kg P ha^{-1} in wet years.

SUMMARY

Phosphorus should not be a yield limiting factor for wheat production. Phosphorus is a relatively immobile nutrient, not subject to leaching losses. The loss mechanisms are mainly through soil erosion and that removed in the harvested portion of the crop. Phosphorus fertilization is an investment that will pay dividends for several years and should be considered a capital improvement to the land. Therefore, a program to build soil P to a level adequate for maximum crop yield potential and maintain it at this level will probably be the most profitable in the long-term. Establishing a soil P level adequate to eliminate P as a deficient crop nutrient can be accomplished by one of two methods: 1) by applying a one-time application of P, either broadcast or band, that is sufficient to raise the soil test P level to an optimum level; or 2) by applying smaller rates of P, either broadcast or band, for several crop years.

RESEARCH NEEDS

Future research regarding residual fertilizer P in soils needs to consider how a farmer might apply high enough rates of P fertilizer to eliminate P as a deficient nutrient in crop production systems while maintaining an economically sustainable system in the short-term. Data suggest that high P rates (90 kg ha^{-1}) are economical in the long-term (> 2 yr) on P deficient soils. Other factors that need to be evaluated in regard to residual P include:

1. Evaluating a one-time, high rate application of P fertilizer as one method of managing P needs of crops grown with reduced- and no-till systems for several years.

2. Developing methods to credit residual P effectiveness when considering P fertilization needs, economics, and P fertilizer use efficiency.

3. Developing models for different soils and cropping systems to predict P fertilization effects on soil test P levels, decline in soil test P level with time after P fertilization, and when future additions of P may be needed.

4. Developing soil test-yield relationships for different soils by establishing different soil test P levels with one-time applications of variable P rates up to at least 200 kg P ha^{-1}, and then measuring crop response to each residual P level utilizing optimum farm management practices such as those used with the MEY concept.

5. On soils that already have high soil P levels, determining how long these soils can supply adequate levels of available P for optimum crop yields before P fertilization is required.

6. Evaluating the effects of P placement (broadcast versus band) on residual P availability to crops over time.

7. Developing procedures to credit soil test P levels for residual P fertilizer that had been previously banded when making P fertilizer recommendations.

8. Developing computer models/systems to variably apply P fertilizer by soil type and need rather than on a field basis, giving credit for previously applied (residual) P fertilizer (a budget type system).

9. Developing innovative methods to eliminate P as a deficient nutrient for crop production, which give credit for residual P fertilizer effects, while maintaining short-term economic sustainability and low labor-machinery requirements.

10. Evaluating the effectiveness/efficiency of residual P availability for crop production versus recently applied (<2 months) P fertilizer.

11. Evaluating the need for higher than normal P rates on more soil types, especially when high yield crop management practices are being used.

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