I. ALFALFA YIELD RESPONSE TO METHOD AND TIMING OF APPLIED PHOSPHORUS

II. EFFECT OF DUAL APPLIED PHOSPHORUS AND GYPSUM ON WHEAT FORAGE AND GRAIN YIELD

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CHAPTER I

ALFALFA YIELD RESPONSE TO METHOD AND TIMING OF APPLIED PHOSPHORUS

ABSTRACT

Past experience in the Southern Great Plains indicates that initial and maintained soil fertility levels strongly affect long-term production of alfalfa (*Medicago sativa* L.). Presently, there are indications that phosphorus (P) fertilizers should be applied at two to three times the annually recommended rate at the time of establishment when the fertilizer can be incorporated. Preplant band-applied P fertilizer may also provide increased long-term benefit by reducing soil-fertilizer P reactions. The objectives of this work were to evaluate the effect of alternative methods and timing of P fertilizer application on alfalfa forage production and to evaluate the long-term persistence of P fertilizer treatments. A 6-yr experiment was conducted in Chickasha, OK, from 1993 to 1998. Three P sources were evaluated, triple superphosphate, diammonium phosphate, and ammonium polyphosphate. Methods of application evaluated were an annually applied rate of 49 kg P ha^{-1}, a biennially applied rate of 98 kg P ha^{-1}, and a single, preplant rate of 293 kg P ha^{-1}. Also included were 293 and 98 kg P ha^{-1} rates that were injected preplant and

biennially, respectively. Single applications of high rates of preplant fertilizer P, either broadcast and incorporated or injected in a band, resulted in higher yields than conventional annually applied rates. This work indicates that in high yielding environments (e.g. irrigated) alfalfa may respond to P-fertilizer inputs above the conventional levels indicated by calibrated soil tests. Additionally, high preplant or biennial P fertilizer rates, either broadcast and incorporated or injected in a band, may provide a P fertility foundation with the potential for sustaining alfalfa yields for several years.

INTRODUCTION

Alfalfa (*Medicago sativa* L.) is a perennial, legume crop produced for forage in Oklahoma. It is preferred over many other forage legumes due to its high yield potential, protein content, and palatability. Uses for alfalfa vary; however, the crop is produced mainly as a dairy and beef cattle feed. Alfalfa is one of the most important cash commodities for Oklahoma producers, generating approximately $150 million annually. The high cash value of this crop emphasizes the importance of management decisions such as variety selection, soil fertility, pest control, harvesting, and marketing. Past experience in the Southern Great Plains indicates that factors most strongly affecting long-term production of alfalfa are often initial and maintained soil fertility levels.

Site selection and pH maintenance are important when establishing alfalfa. For optimum alfalfa production, the site should be a deep, well-drained, medium textured (loamy or sandy loam) soil. Alfalfa roots can penetrate up to 7.6 m in a deep soil (Caddel et al., 1996). This is one of the strong characteristics of alfalfa that can be limited in a shallow soil. Alfalfa requires approximately 15 cm of available water per ton of forage produced and deep, medium textured soils usually have sufficient water holding capacity for alfalfa (Caddel et al., 1996). However, adequate drainage is also important for optimum microbial activity and disease prevention. Soil pH must also be considered as alfalfa is more sensitive to acid soil than many other crops. The preferred pH range for alfalfa production is 6.2 to 7.5, with 6.8 being optimum (Allen and Johnson, 1993). Allowing soil pH to decrease below this range may result in both diminished quality and reduced yield. Soil nutrient levels also must be monitored for successful alfalfa production.

Alfalfa forage generally contains 3 to 4% nitrogen (N), but because it is a legume and acquires most of its own N via rhizobial symbiosis, N fertilization on established alfalfa stands is not a common practice. Phosphorus and potassium (K) make up 0.2 to 0.5% and 1 to 2% of alfalfa forage, respectively (Bickoff et al., 1972). This indicates that an 11 Mg alfalfa crop removes 22 to 55 kg P ha^{-1} and 110 to 220 kg K ha^{-1} from the soil annually, some of which must be replaced through fertilization. When P and K fertilizers are applied to established alfalfa stands, they are normally broadcast on the soil surface. Due to the immobile nature of P and K, this practice does not maximize nutrient availability to the existing root system. Ideally, immobile nutrients should be incorporated to improve their positional availability.

Sheard et al. (1971) demonstrated that band placement of P near the seed is also an effective method of fertilization at establishment of alfalfa stands. Banding not only applies the nutrient where there is the greatest chance for root contact, but also reduces the surface area of the fertilizer in direct contact with the soil which limits the potential for formation of insoluble precipitates. Reducing soil-fertilizer P reactions can provide increased long-term benefit from fertilizer P. However, in-season band-applications to established alfalfa have been reported to have negative effects on fertilizer efficiency due to mechanical damage to the roots, soil drying, and possible disruption of N fixation (Leyshon, 1982). Simons et al. (1995) also reported band-applications of P into established alfalfa stands to have no benefit over broadcast applications.

The dilemma faced when dealing with perennial crops like alfalfa, is whether to apply two to three times the recommended rate at the time of establishment when it can be incorporated, or to broadcast smaller amounts annually. Moyer (1992) found that high rates of P fertilizer applied (320 kg P_2O_5 ha^{-1}) at planting resulted in increased forage yield for several years. Malhi et al. (1992) reported residual effects of single, large P applications to result in increased yields for five years.

Economic comparisons of these different approaches are complex, taking into consideration such factors as initial and annual values of the crop and fertilizer, as well as interest rates for capital expended preplant as opposed to annually for fertilizer. It would seem that single, large preplant rates of P would have to produce yields at least equal to those resulting from annual applications over the life of the stand or a period of reasonable comparison to be profitable. Of additional concern is the effect of large additions of N when ammonium phosphates are applied at high preplant rates. High rates of N may reduce the effectiveness of rhizobial N-fixation and also encourage growth of non-legume weeds leading to lower alfalfa production. The objectives of this work were to evaluate the effect of alternative methods and timing of P fertilizer application on alfalfa forage production and to evaluate the long-term persistence of P fertilizer treatments.

MATERIALS AND METHODS

One experiment was established in September 1992, at the South Central Research Station in Chickasha, OK, on a Dale silt loam soil (fine-silty, mixed, thermic Pachic Haplustoll). Initial soil sampling of the entire area was used to identify a homogenous area where P levels were low to medium (Mehlich III of 15 mg kg^{-1}). A rate of 464 kg K ha^{-1} was applied to the entire experimental area at establishment. All other nutrients and soil pH were adequate (Table 1). Sources of P evaluated were triple superphosphate (TSP, 0-46-0), diammonium phosphate (DAP, 18-46-0), which were both dry sources, and ammonium polyphosphate (APP, 10-34-0), a liquid source. The experiment was maintained for six years, with all treatments receiving a total of 293 kg P ha^{-1} by the sixth year.

Phosphorus fertilizer applications were the following: no P applied, 49 kg P ha^{-1} applied annually as DAP (common producer practice), 98 kg P ha^{-1} applied at establishment with subsequent 98-kg P ha^{-1} applications in the third and fifth year of the study (all sources), and 293 kg P ha^{-1} applied at establishment (all sources). All sources were broadcast applied using a dry fertilizer spreader or a conventional liquid applicator. The rates applied at planting were incorporated while rates applied in subsequent years were not.

Method of P application was evaluated using two treatments involving APP being injected 15-cm deep into the soil for both preplant and subsequent application dates (293 kg P ha^{-1} at planting or 98 kg P ha^{-1} at planting with additional 98-kg P ha^{-1} injections into the established alfalfa in years three and five). This was accomplished using a custom-built liquid-fertilizer applicator which was equipped with five integrated coulter-knife units (2-cm wide) spaced 45-cm apart. Also included in the treatment structure were annual applications of K and gypsum (464 kg ha^{-1} and 56 kg S ha^{-1}, respectively). The complete treatment structure is reported in Table 2.

A randomized complete block experimental design with four replications was employed. Plot size was 27 by 91 m. The alfalfa variety 'Garst 630' was planted to the entire area at a rate of 20 kg ha^{-1}. Supplemental water via irrigation, insecticides, and herbicides were administered as needed. An average of five forage harvests were obtained each year from 1993 to 1998. At each harvest, average stem counts for each treatment were collected from four randomly selected 0.1 m^2 areas within each plot to estimate stand density. A 5.0 m^2 area from the center of each plot was harvested at each cutting using a 'Carter' forage harvester. Following each cutting, the remaining forage was harvested and removed from the entire experimental area using a conventional swather and baler. Alfalfa forage samples were subsampled for moisture determination and dry matter yield was calculated for all treatments. Composite surface soil samples (0 to 15-cm deep) were collected from each plot in February 1999, following completion of the experiment. Samples were analyzed for P and K (Mehlich, 1984) and pH (1:1 soil water). Significant treatment differences for alfalfa yield and soil test P, K, and pH were determined using analyses of variance and appropriate contrasts (SAS, 1990).

RESULTS AND DISCUSSION

Alfalfa yields (averaged over treatment) in this trial were approximately 14.3 Mg ha^{-1} annually over the six-year study. Although overall stand density had decreased by the sixth year from 366 stems m^{-2} in 1993 to 194 stems m^{-2} in 1998, yield levels had not diminished from those obtained in the early years of the study. No yield response to additional S was observed in any year of the study.

Response to Applied K

A yield increase due to additional K was observed only in the third year of the study (16.1 vs. 18.3 Mg ha^{-1}; $p<0.05$). Soil samples were collected from selected treatments (0 to 15-cm deep) following the final harvest of 1995. Analysis of the soil samples revealed that, according to soil test calibration, no treatments were deficient in K, despite the yield increase as a result of 464 kg K ha^{-1} being added annually. This indicated that application of more K than identified from standard soil tests may be beneficial for alfalfa forage production. However, alfalfa is a crop that will remove more K than is required for maximum yield (Johnson et al., 1997), so applying several years supply of K to the crop would probably not be economical. In addition, a total of 928 kg K ha^{-1} had been applied before the yield increase was observed, therefore it is difficult to determine how much K should be applied to constitute a K-rich environment. The entire experimental area received a broadcast application of 464 kg K ha^{-1} in the fourth year (1996) to remove K as a response variable.

Response to Applied P

No forage yield differences due to source of applied P were observed in any year of the study. For discussion regarding yield response to broadcast applications of P, treatments that received P as DAP, often the most cost-effective source of P, will be used. By-year yield responses were difficult to analyze due to unequal P rates that had been applied each year. Therefore, in addition to total (6-yr) production response, by-year yield responses to fertilizer applications in only the first (to evaluate initial response to P rate), fourth (total annually and biennially applied rates were comparable), and final year (all treatments had received an equal P rate) are discussed.

First Year (1993) Results

Initial soil tests identified the site as having a medium P supplying capacity (80 % sufficient in P) and that an annual rate of about 39 kg P ha^{-1} should remove P deficiency as a yield limiting factor. The common producer practice of applying the annual soil test recommended or slightly greater rate of 49 kg P ha^{-1}, resulted in a 4% yield increase compared to not applying P (Figure 1). Alfalfa forage yield increase nearly doubled when the applied rate was doubled to 98 kg P ha^{-1} ($p<0.05$; Figure 1). Alfalfa yield was further increased in the first year when 293 kg

P ha^{-1} was broadcast and incorporated at establishment (Figure 1). The fact that the 293-kg rate, which was six times the amount required to reach 100% sufficiency according to the soil test calibration, maximized alfalfa forage production (15.7 Mg ha^{-1}) indicates that a P-rich growing environment (supply exceeds that normally required for 100% sufficiency) is beneficial for alfalfa establishment and initial productivity.

Injection of 98 kg P as APP ha^{-1} at establishment resulted in a yield increase 60% greater than that obtained using the conventional 49-kg P as DAP ha^{-1} broadcast rate ($p<0.05$; Figure 1). However, injecting APP was not better than broadcasting DAP at the 98-kg rate (Figure 1). Preplant injection of 293 kg P as APP ha^{-1} was the second highest yielding treatment (15.0 Mg ha^{-1}), resulting in 76% of the yield increase obtained when the same rate of DAP was incorporated preplant ($p<0.05$; Figure 1).

Fourth Year (1996) Results

In the fourth year, an 18% yield increase resulting from the 98-kg biennial (196 kg P ha^{-1} applied total) broadcast treatment was greater than the increase resulting from the annual 49-kg P ha^{-1} (196 kg P ha^{-1} applied total) treatment ($p<0.05$; Figure 2). The yield increase from the biennial treatment was also greater than the increase observed as a result of the single preplant application of 293 kg P ha^{-1} ($p<0.05$; Figure 2). A benefit to injecting P fertilizer compared to broadcast was observed in 1996. Injected applications of P resulted in the greatest yield increases ($p<0.05$; Figure 2) with no yield difference occurring between 293 kg P ha^{-1} (injected preplant) and 196 kg P ha^{-1} (applied using two biennial injections of 98 kg P ha^{-1}). Similar to the broadcast treatments, the 293-kg preplant injected treatment did not result in increased yield compared to that obtained by applying two 98-kg injections. Additionally, the 293-kg broadcast treatment was not different from the conventional annual application, which had received a total of 196 kg P ha^{-1} (Figure 2). This suggested that the residual effects from the single, preplant broadcast rate of 293 kg P ha^{-1}, had begun to diminish by the fourth year of the study.

Sixth Year (1998) Results

By 1998, all treatments had received a total of 293 kg P ha^{-1}. The common producer practice of applying 49 kg P ha^{-1} annually increased alfalfa forage yield 15% in the final year of the study (Figure 3) compared to only 4% in the first year (Figure 1). By applying slightly more than what would be used by the crop, soil fixation capacities were satisfied, plant available P foundations were established, and greater yield increases were being observed after six years. A similar effect was observed when 98 kg P ha^{-1} was applied biennially, as increased yields rose from 9% in 1993 (Figure 1) to 19% in 1998 (Figure 3). Conversely, when 293 kg P ha^{-1} (a six-year supply) was applied preplant, yield increases were greatest in the first year (Figure 1) and had diminished considerably by the sixth year of the stand (Figure 3). Despite the poor production in the sixth year, the single, high-rate preplant application resulted in yield increases over the six-year period greater than the annually applied treatment and equal to those obtained using the biennially broadcast treatment ($p<0.05$; Figure 4). This indicates a greater P use efficiency associated with larger P rates combined with fewer applications over the life of the alfalfa stand.

Although the biennially injected treatment exhibited a burst of production during 1996 (Figure 2), no benefit to injecting P fertilizer biennially was observed when compared to broadcast applications in the final year of the study or over the six-year period ($p<0.05$; Figures 3 and 4). However, the single, preplant injection of 293 kg P ha^{-1} resulted in the highest total yield increase compared to all broadcast treatments ($p<0.05$; Figure 4). Figure 5 indicates that 293 kg P ha^{-1} injected preplant was also one of the fertilizer application strategies that exhibited stability by maintaining consistent yield increases throughout the course of the study. Six-year alfalfa forage yield response trends for annual and biennial applications are also illustrated in Figure 5. The only treatment resulting in a significant slope was the 293-kg P ha^{-1} broadcast incorporated rate ($p<0.05$, Figure 5). Although this treatment resulted in the highest initial yields, its level of production was not sustained over the six-year period.

Composite soil samples collected in February 1999 revealed no differences in soil test K or pH for any treatments evaluated in the study (Table 3). Differences in soil test P did, however, exist among treatments ($p<0.05$; Table 3). After six years of production, the treatment that had received no P, and had produced the least forage, had decreased in P sufficiency from 80% to 60% (soil test P level of 7.3 mg kg^{-1}; Table 3). The highest yielding treatment (293 kg P ha^{-1} injected preplant) had the lowest residual soil test P (12.8 mg kg^{-1}; Table 3) of any treatments that had received fertilizer. The broadcast incorporated rate of 293 kg P ha^{-1} was not different, with soil test P of 15.5 mg kg^{-1} (Table 3). These soil test levels indicated that these treatments, regarding available P, had returned to their original condition of approximately 80% sufficiency. Meanwhile, the sufficiency of the treatments receiving annual and biennial applications of P had increased to > 97% (soil test P > 28 mg kg^{-1}; Table 3).

Therefore, this work indicates that in high yielding environments (e.g. irrigated) alfalfa may respond to P-fertilizer inputs above the conventional levels indicated by calibrated soil tests. Additionally, high preplant or biennial P fertilizer rates, either broadcast and incorporated or injected in a band, may provide a P fertility foundation with the potential for sustaining alfalfa yields for several years.

REFERENCES

Allen, E. and G. Johnson. 1993. OSU Soil Test Interpretations. Oklahoma State University Extension Facts 2225.

Bickoff, E.M., G.O. Kohler, and D. Smith. 1972. Chemical composition of herbage. Pages 247-282 *in* C.H. Hanson, ed. Alfalfa science and technology. ASA-CSSA-SSSA, Madison, WI.

Caddel, J., J. Stritzke, P. Mulder, G. Johnson, C. Ward, R. Huhnke, and R. Berberet. 1996. Alfalfa Stand Establishment Questions and Answers. Oklahoma Coop. Extension Circular E-949.

Johnson, G.V., W.R. Raun, H. Zhang, and J.A. Hattey. 1997. Oklahoma Soil Fertility Handbook. Fourth ed. Dept. of Agron., Okla. Agric. Exp. Sta., Okla. Coop. Ext. Serv., Div. of Agric. Sci. and Nat. Res., Oklahoma State University, Stillwater, OK.

Leyshon, A.J. 1982. Deleterious effects on yield of drilling fertilizer into established alfalfa stands. Agron. J. 74: 741-743.

Malhi, S.S., M.A. Arshad, K.S. Gill, and D.K. McBeath. 1992. Response of alfalfa hay yield to phosphorus fertilization in two soils in central Alberta. Commun. Soil Sci. Plant Anal. 23: 717-724.

Mehlich, A. 1984. Mehlich no.3 extractant: A modification of Mehlich no. 2 extractant. Commun. Soil Sci. Plant Anal. 15:1409-1416.

Moyer, J.R. 1992. Alfalfa yields in establishment and subsequent years after herbicide and phosphorus application during establishment. Can. J. Plant Sci. 72: 619-625.

SAS Institute. 1990. SAS/STAT user's guide. Release 6.03 ed. SAS Inst., Cary, NC.

Sheard, R.W., G.J. Bradshaw, and D.L. Massey. 1971. Phosphorus placement for the establishment of alfalfa and bromegrass. Agron. J. 63: 922-927.

Simons, R.G., C.A. Grant, and L.D. Bailey. 1995. Effect of fertilizer placement on yield of established alfalfa stands. Can. J. Plant Sci. 75: 883-887.

Table 1. Initial soil test characteristics for Chickasha, OK, 1992.

NO_3-N	P	K	pH
--------- mg kg^{-1} --------			
13.6	15.1	163	6.6

NO_3-N - 2M KCl extract; P, K - Mehlich III; pH - 1:1 soil-water

Table 2. Treatment structure including method, source, and timing of P, K, and S applications employed at Chickasha, OK, 1992.

Trt.	Placement†	Source‡	---------- P Timing ---------- preplant	yrs 3 and 5	K§	S¶
			------ kg P ha^{-1} ------		--- kg ha^{-1} ---	
1	BC	TSP	98	98	0	0
2	BC	TSP	293	0	0	0
3	BC	DAP	98	98	0	0
4	BC	DAP	293	0	0	0
5	BC	APP	98	98	0	0
6	BC	APP	293	0	0	0
7	INJ	APP	293	0	0	0
8	INJ	APP	98	98	0	0
9	CK	---	0	0	0	0
10	BC	DAP	49	49 (yrs 2, 3, 4, 5, 6)	0	0
11	BC	DAP	98	98	0	56
12	BC	DAP	98	98	464	0

† - BC – broadcast incorporated preplant (not incorporated in subsequent years), INJ – injected 15-cm deep, CK – check (no nutrients applied); ‡ - TSP – triple superphosphate (0-46-0), DAP – diammonium phosphate (18-46-0), APP – ammonium polyphosphate (10-34-0); § - K broadcast applied each year as 0-0-62; ¶ - S broadcast applied each year as gypsum.

Table 3. Soil test P, K, and pH determined on composite surface samples (0 to 15-cm deep) collected from Chickasha, OK, 1998, following six years of alfalfa production.

Treatment	P	K	pH
---- kg P applied ha^{-1} ----	--- mg kg^{-1} ---		
None	7.2	358	6.9
49 broadcast annually	38.7	340	6.6
98 broadcast biennially	28.9	352	6.5
293 broadcast preplant	15.5	351	6.6
98 injected biennially	39.2	347	6.4
293 injected preplant	12.8	339	6.6
SED	8.5	26	.08

P, K - Mehlich III; pH - 1:1 soil-water; SED - standard error of the difference between two equally replicated means

Figure 1. Percent alfalfa forage yield increase over the check (no P applied) in the first year of the study (1993) as a result of preplant applied rates of P. SED = standard error of the difference between two equally replicated means.

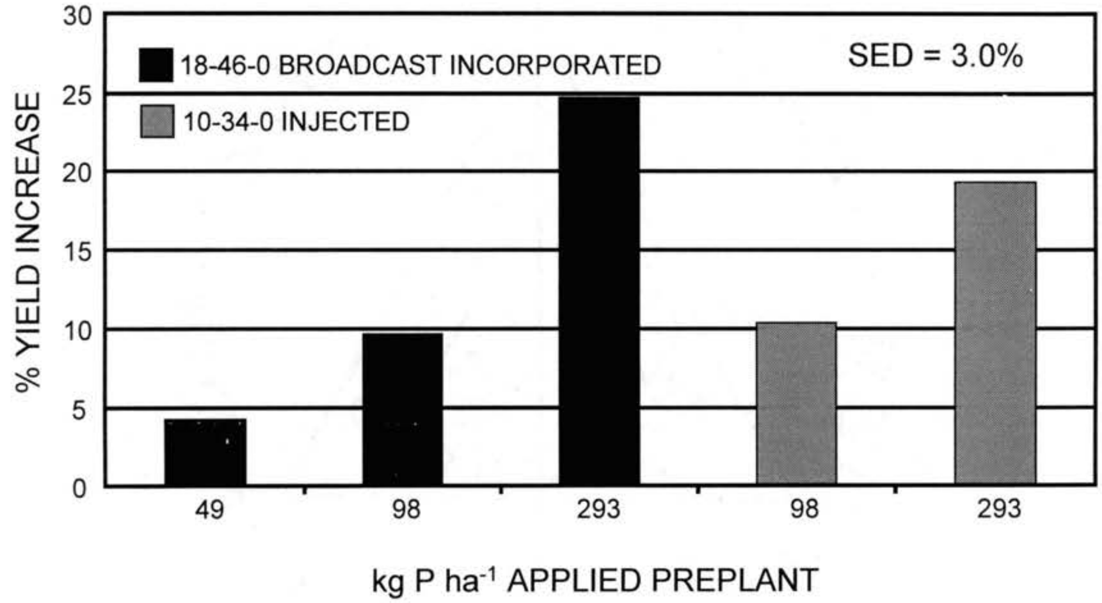


Figure 2. Percent alfalfa forage yield increase over the check (no P applied) in the fourth year of the study (1996). Treatments had received a total of 196 or 293 kg P ha^{-1} applied using different timing and application methods. SED = standard error of the difference between two equally replicated means.

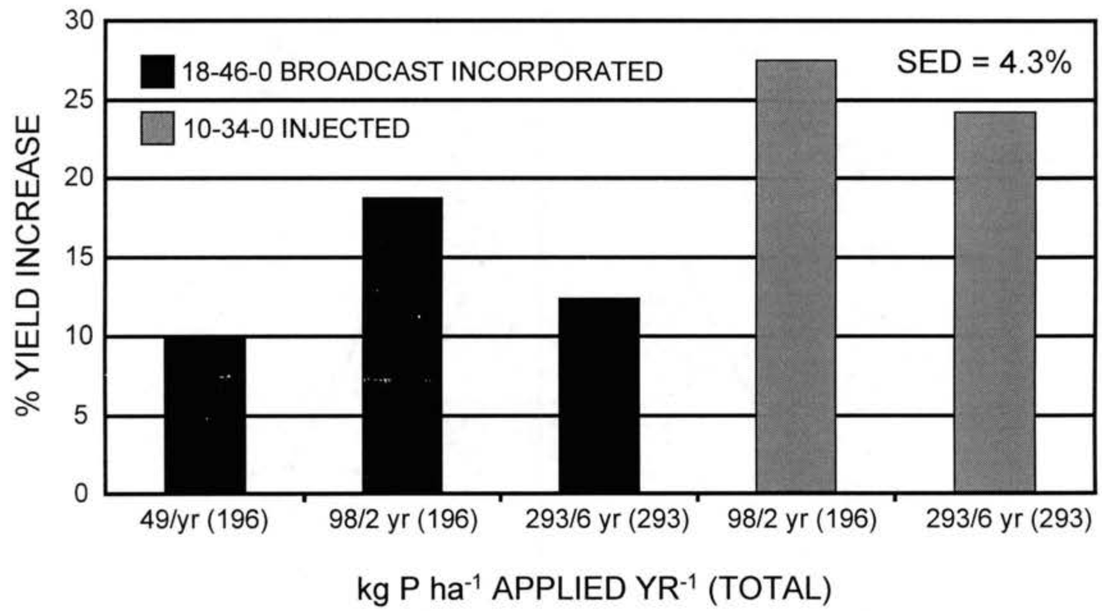


Figure 3. Percent alfalfa forage yield increase over the check (no P applied) in the final year of the study (1998). All treatments had received a total of 293 kg P ha^{-1} applied using different timing and application methods over a six-year period. SED = standard error of the difference between two equally replicated means.

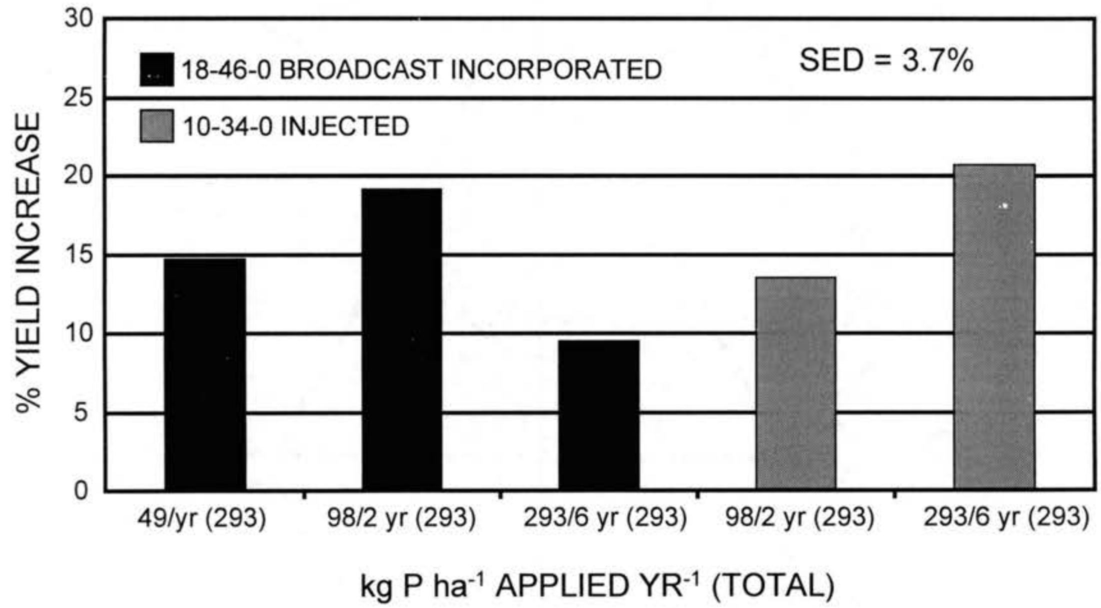


Figure 4. Total alfalfa forage yield increases over the check (no P applied) observed over a six-year period (1993 to 1998) as a result of different timing and methods of application of P fertilizer. SED = standard error of the difference between two equally replicated means.

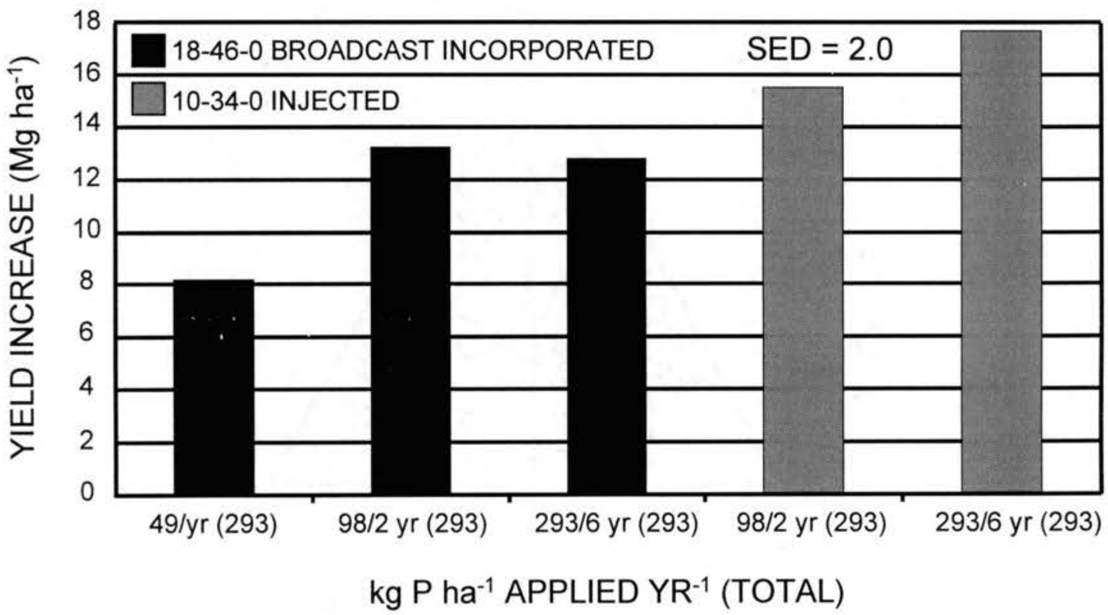
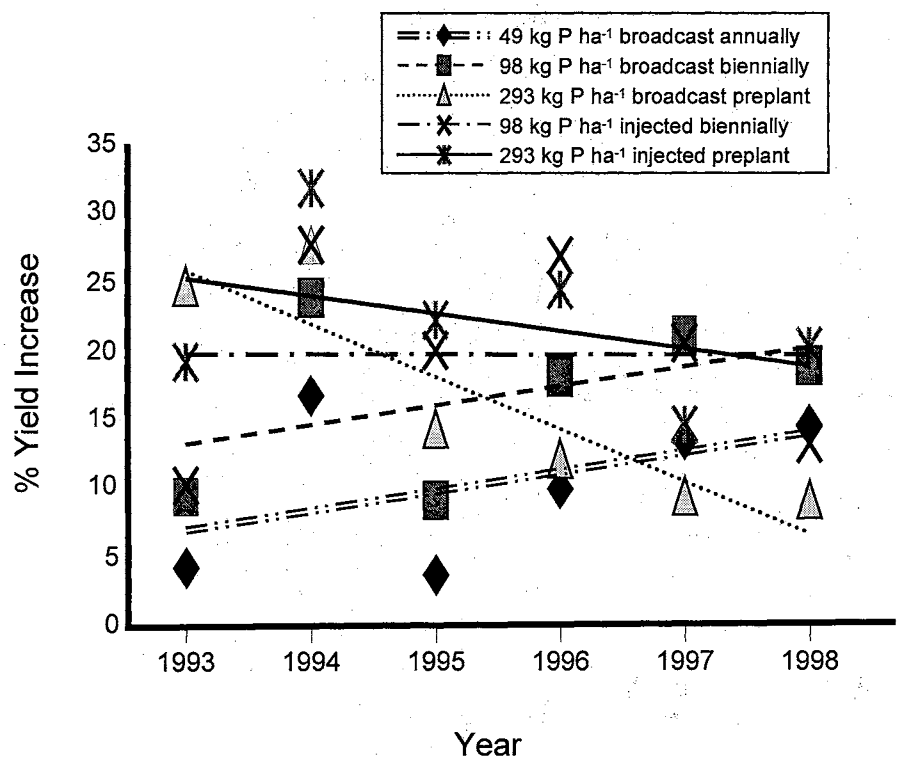


Figure 5. Response trends of alfalfa forage yield increases over the check (no P applied) over a six-year period (1993 to 1998) as a result of P fertilizer application methods.



CHAPTER II

EFFECT OF DUAL APPLIED PHOSPHORUS AND GYPSUM ON WHEAT FORAGE AND GRAIN YIELD

ABSTRACT

Winter wheat (*Triticum aestivum* L.) production on acid soils is greatly affected by P availability. At low pH (below 5.5), Fe and Al react with P to form highly insoluble compounds that severely reduce the amount of plant available P. Previous research suggested that supersaturating the soil with respect to Ca^{2+} could induce precipitation of applied P as dicalcium phosphate (DCP) or dicalcium phosphate dihydrate (DCPD) which would slowly become plant available with time. The objective of this study was to determine the effect of dual-band applications of P and gypsum on winter wheat forage and grain yield. Methods of application included P and gypsum banded with the seed, P and gypsum broadcast, and P banded and gypsum broadcast at rates of 29 and 58 kg P ha^{-1} and 22 and 44 kg S as gypsum ha^{-1}. Sources of P included diammonium phosphate (DAP; 18-46-0) and triple superphosphate (TSP; 0-46-0). Grain and forage yields increased when P was applied. Dual-band applications of P and gypsum increased wheat grain and forage yields compared

to P banded without gypsum, and P banded and gypsum broadcast. When DAP was the P source, the N-P band reduced yields compared to P banded alone or the N-P-gypsum band. This suggests that gypsum should be included in the band for maximum benefit. Precipitation of DCPD and DCP may have taken place within the dual P-gypsum band, reducing fertilizer P fixed as Fe or Al hydroxides thus increasing long-term P availability for winter wheat forage and grain production on acid soils.

INTRODUCTION

Winter wheat (*Triticum aestivum* L.) production on acid soils is greatly affected by P availability. At low pH (below 5.5), Fe and Al react with P to form highly insoluble compounds such as variscite and strengite, thus severely reducing the amount of plant available P. Phosphorus can also adsorb to surfaces of Fe and Al oxides and clay minerals. This inherent fixation capacity of soils must be satisfied in order to build available P levels for optimum P nutrition and efficient management of fertilizer-P.

Fertilizer-P is generally in a readily available form such as monocalcium phosphate (MCP, $Ca(H_2PO_4)_2$), but can be quickly converted to slowly available forms such as dicalcium phosphate dihydrate (DCPD, $CaHPO_4{\bullet}2H_2O$) and dicalcium phosphate (DCP, $CaHPO_4$). Dicalcium phosphate dihydrate was found to form in soils having a water-soluble Ca to Mg ratio of approximately 1.5 or greater when orthophosphates were added to soils with varying Ca and Mg levels (Racz and Soper, 1967). Lindsay (1979) reported that MCP, which is the principal P source in ordinary superphosphate (OSP) and triple superphosphate (TSP), contained sufficient Ca^{2+} to precipitate half of the P as DCP or DCPD. Lindsay (1979) also indicated that inclusion of cations such as NH_4^+, K^+, Ca^{2+}, and Mg^{2+} in fertilizers enabled these cations to be included among the initial reaction products. This research suggested that supersaturating the fertilizer band with respect to Ca^{2+} could induce precipitation of P as DCP or DCPD, which would slowly become plant available with time.

Gypsum ($CaSO_4 \bullet 2H_2O$) is a compound that if applied in a dual-band with P would provide an abundant supply of Ca^{2+} upon dissolution. Raun and Barreto (1991) reported maize (*Zea mays* L.) yields in Guatemala to be maximized when N, P, and S were applied in a joint-band. They hypothesized that precipitation of DCP and DCPD did, in fact, take place within the joint-band, subsequently reducing the amount of P fixed as Fe or Al compounds. Dual-band applications of gypsum, in addition to precipitating P, can also serve as an added source of S.

Sulfur deficiencies in Oklahoma soils are rare due to adequate amounts of S being added annually in the form of rainfall. However, concerns regarding S deficiencies have become more prevalent in winter wheat production systems where both wheat forage and grain are removed. Therefore, the objective of this study was to determine the effect of dual-band applications of P and gypsum on winter wheat forage and grain yields.

MATERIALS AND METHODS

One field experiment was established in the fall of 1993 at the Oklahoma State University Eastern Research Station, Haskell, Oklahoma. The soil at this site was classified as a fine, mixed, thermic Mollic Albaqualf. Initial soil test characteristics are reported in Table 1. The experimental design employed was a randomized complete block with three replications. Plot size was 5.0 by 10.6 m.

Methods of application included P and gypsum banded together with the seed, P banded with the seed and gypsum broadcast, P and gypsum broadcast, and corresponding check treatment combinations where neither P nor gypsum was applied. Two P sources, triple superphosphate (TSP, 0-46-0) and diammonium phosphate (DAP, 18-46-0), were used at rates of 29 and 58 kg P ha^{-1}. Gypsum (prilled source, 17%S) was applied at rates of 22 and 44 kg S ha^{-1}.

Broadcast gypsum treatments were applied by hand, while broadcast P and N treatments were applied using a calibrated dry fertilizer spreader. Nitrogen was applied preplant and incorporated at a rate of 112 kg N ha^{-1} to all plots using ammonium nitrate (34-0-0). Nitrogen rates were adjusted accordingly for carrier N in DAP treatments. A John Deere 450 grain drill was used to apply the fertilizer treatments which were banded with the seed. The 450 grain drill contained separate compartments for seed and fertilizer which could be individually calibrated. Six of the treatments required banding both P and gypsum together with the seed. To accomplish this, proportional mixtures of the two sources were prepared to meet the rate requirements for each nutrient as per treatment definition (Table 2). The fertilizer compartment was then calibrated for each mixture. To eliminate cross-contamination resulting from different sources and mixtures being applied from the same fertilizer compartment, any remaining fertilizer was removed using a portable vacuum after each treatment application. The remaining plots (no fertilizer applied and broadcast fertilizer applications) were subsequently planted using the 450 grain drill. Fertilizer treatments were applied for three years (1993 through 1995), with the 1996-97 and 1997-98 crop years being harvested for analysis of residual effects.

The wheat variety 'P2163' was used each year and was planted in early October at a rate of 88 kg ha^{-1} in 21-cm rows. This variety has been shown to have moderate tolerance to soil acidity. Wheat forage was collected at Feekes physiological stage 10 (late-April, Large, 1954) from a 4.5 m^2 area using a modified rotary mower harvester (Norton et al., 1996), and subsampled for moisture determination. Grain yields were determined by harvesting the center 2.0 m over the entire length of each plot using a Massey-Ferguson 8XP plot combine. Wheat straw was uniformly redistributed in all plots each year. No tillage practices were performed during the summer, so as not to disturb the fertilizer band. Weed control for the entire experimental area was accomplished by applying 2,4-dichlorophenoxyacetic acid as needed. The plots were disked prior to planting at a depth shallow enough to provide minimal disturbance of the band and still prepare an adequate seedbed.

Following the 1997 grain harvest, composite soil samples (50, 2-cm diameter cores; 0 to 15-cm deep) were taken from each plot. Soil cores were taken within

2.5 cm of the rows in an attempt to accurately sample the fertilizer band. Available soil P was determined colorimetrically (Watanabe and Olsen, 1965) using Mehlich III (pH = 2.4; Mehlich, 1984), Bray-Kurtz P1 (pH = 3.2; Bray and Kurtz, 1945), and distilled water (pH = 7.0; Olsen and Sommers, 1982) extraction procedures. Statistical analysis of the data was performed using procedures outlined by the SAS institute (SAS, 1990).

RESULTS AND DISCUSSION

Except for 1995 (severely drought affected), both broadcast and band-applied P resulted in increased yields in each year of the study for both forage and grain production. This response continued to be present in the first residual year (1997) indicating that P fertility foundations had been established as a result of earlier fertilizer applications (1993 through 1995). However, the second residual harvest in 1998 resulted in no grain or forage yield differences, not necessarily due to residual P depletion, but rather soil NO_3-N and pH reaching insufficient levels (5.6 kg ha^{-1} and 4.6, respectively).

1994 Results

Forage yields increased when up to 58 kg P ha^{-1} was banded with the seed or broadcast incorporated (Table 3). At each rate of applied P (29 and 58 kg ha^{-1}) the forage yield response to band-applied P was greater than the response to broadcast P ($p<0.01$; Table 3). No response to applied gypsum, either applied alone or dual-banded with P, was observed in the first year of the study. No differences in forage yield were observed when N was included in the P-gypsum band compared to P and gypsum banded together without N (Table 3). However, when N and P were banded together and gypsum was broadcast, forage yield was lower than when N, P, and gypsum were banded together or P and gypsum were banded together without N ($p<0.01$; Table 3).

It is hypothesized that, in addition to having P precipitated in initially unavailable forms (DCP and DCPD), NH_4^+ may also be involved in forming initial precipitated P products when DAP is used as opposed to TSP. Savant and Racz (1973) have discussed the importance of initial P reaction products, particularly metastable intermediate products that are expected to dissolve with time. Apparently, N applied within the P-band in the absence of gypsum is having a negative effect on plant availability of the precipitated products. The presence of an abundance of Ca^{2+} in the band when gypsum is included may result in DCP and DCPD being the preferred precipitates, which reduces the chance of banded N inducing precipitation of unavailable P compounds. This supports the findings of Raun and Barreto (1991) who reported that gypsum needs to be included in the N-P band rather than broadcast for maximum benefit.

Grain yield response to band-applied P in 1994 was different than forage response in that increases were only observed up to 29 kg P ha^{-1} with no yield difference between 29 and 58 kg P ha^{-1} (Table 3). The response to broadcast P was similar to forage response, increasing up to 58 kg P ha^{-1} (Table 3). No difference in grain yield at the 58-kg P ha^{-1} rate was observed when comparing band-application to broadcast (Table 3). However, at the 29-kg P ha^{-1} rate, band-applied P resulted in higher grain yields than broadcast P ($p<0.05$; Table 3). As was observed with forage production, no response to gypsum being included in the band was observed for grain yield. The forage yield reduction resulting from banding N and P without gypsum was also observed for grain yield ($p<0.05$; Table 3).

1995 Results

Forage yield response in the second year followed the same trend as grain yield in 1994, a quadratic yield increase due to band-applied P (no difference between 29 and 58 kg P ha^{-1}) and a linear yield increase as a result of broadcast-applied P ($p<0.01$; Table 3). A benefit to band-applied P compared to broadcast was observed only at the 29-kg P ha^{-1} rate ($p<0.05$; Table 3). No effect of gypsum, broadcast or band-applied, was observed in 1995. The forage yield reduction associated with the N-P band without gypsum in the 1994 harvest continued to be present in 1995 ($p<0.05$; Table 3).

Grain yields in 1995 were devastated by drought with the highest yielding treatments producing only slightly over 1000 kg ha^{-1}. No response to applied P or gypsum, band or broadcast, was observed in 1995. The only treatments resulting in grain yield differences in 1995 were N-P-gypsum band-applied vs. N-P band-applied, which yielded 760 and 1110 kg ha^{-1}, respectively ($p<0.05$; Table 3).

1996 Results

In 1995-96, the third and final crop year that fertilizer treatments were applied, the forage yield response to band-applied and broadcast P remained consistent with the previous year (quadratic and linear increases, respectively). No benefit to band-applications of P was observed in 1996, however, including gypsum in the band did increase forage yields in the third year of the study at the lower P rate ($p<0.05$). The dual-band application of 29 kg P and 22 kg S as gypsum ha^{-1} resulted in a forage yield of 1746 kg ha^{-1} (Table 3). This was a significant increase when compared to 1084 kg forage produced ha^{-1} when P was banded alone and 1002 kg forage produced ha^{-1} when P was banded and gypsum was broadcast (Table 3). No forage yield response to the dual-band was observed at the higher P rate (58 kg P ha^{-1}). No response to gypsum banded alone was observed, suggesting that the effect of gypsum being combined in the band with P resulted in the yield increase.

Since this response was not observed in the first two years of the study, it is possible that the dual-applied P and gypsum could have initially been precipitated in plant unavailable forms. Given that these acid soils are known to have high P fixation capacities, particularly as unavailable Fe or Al hydroxides, dissociation of the $CaSO_4 \bullet H_2O$ in the dual P-gypsum band may have induced precipitation of DCP and DCPD because of the presence of the added Ca^{2+}. Therefore, DCP and DCPD could have slowly become plant available with time, thus reducing the amount of applied P fixed as unavailable Fe or Al hydroxides.

This would explain the increases in yield due to the dual-band in the latter stage of the study.

It is interesting to note that a yield increase similar to the one observed as a result of the dual P-gypsum band was obtained when P and gypsum were both broadcast compared to P banded alone or P banded and gypsum broadcast ($p<0.05$; Table 3). This suggested that P and gypsum placed together, either in a band or on the soil surface, can form P compounds that slowly become plant available. A forage yield response that had been observed in the first two years of the study that was not present in 1996 was the yield reduction associated with including N in a band with P without gypsum. It is possible that applied P had been initially sequestered in some NH_4^+ induced intermediate compound and became plant available by the third year of the study.

Dual-band applications of P and gypsum also resulted in increased grain yields compared to P banded alone or P banded and gypsum broadcast in 1996 ($p<0.10$; Table 3). However, grain yield increases were observed at both rates of P (29 and 58 kg ha^{-1}). Similar to the forage yield increases, no differences in response existed due to rate of gypsum in the band or to gypsum banded alone. At the 58-kg P ha^{-1} rate, the dual-broadcast P-gypsum treatment resulted in yield increases equal to those obtained when P and gypsum were placed in a band together (Table 3). The 29-kg P ha^{-1} dual-broadcast treatment, which had displayed a similar trend in forage production, was not different from the P banded alone or the P banded and gypsum broadcast treatments for grain yield.

Residual Harvest Results (1997 and 1998)

In 1997, forage and grain yield responses to fertilizer treatments applied from 1993 to 1995 were evaluated to assess the residual effect of the dual-band applied P and gypsum. The residual forage harvest in 1997 revealed a quadratic yield response to previously band-applied P ($p<0.01$), but no benefit was observed as a result of the dual-band applications at either P rate. The previously broadcast applied P treatments resulted in increased forage yield up to 58 kg P ha^{-1} ($p<0.01$), showing no yield difference when compared to banding at the 58-kg P ha^{-1} rate. However, at the 29-kg P ha^{-1} rate, banded P treatments resulted in higher forage yield than treatments receiving broadcast P (1428 and 1034 kg ha^{-1}, respectively; $p<0.05$). The N-P-gypsum band showed no residual difference in forage yield compared to P banded alone or a dual-band of P and gypsum.

In 1997, residual grain yield response to applied P increased up to 58 kg P ha^{-1}, indicating that P foundations established through fertilization in previous years had not been depleted ($p<0.01$). The dual-band application of P and gypsum at 58 kg P ha^{-1} continued to result in an increase in grain yield compared to P banded and gypsum broadcast (2940 and 2640 kg ha^{-1}, respectively; $p<0.10$). This residual response suggested continued dissolution of the dual P-gypsum band, resulting in increased amounts of plant available P for grain yield compared to P banded without gypsum. The dual-broadcast application of 58 kg P ha^{-1} and gypsum also resulted in increased yield equal to that obtained from the dual-band application (2950 kg ha^{-1}).

Following the 1997 grain harvest, surface soil analyses were performed for each treatment to determine if dual-band applications of P and gypsum had any effect on residual soil test P compared to P banded without gypsum. At the 29-kg P ha^{-1} rate, all soil P tests indicated that higher levels of extractable P existed in the plots that had received a dual P-gypsum band compared to plots that received only banded P ($p<0.05$; Table 4). No differences in soil test P were observed for any extraction procedure at the 58 kg P ha^{-1} rate or between gypsum rates at either P rate (Table 4).

Subbarao and Ellis (1975) demonstrated that the same P fertilizer could form many different P compounds of different solubilities in soils. Solutions of differing extractant strength can result in different amounts of soil P being detected according to the forms of soil P present. Mehlich III (pH = 2.4) was the most acidic extractant used; therefore, it should provide an estimate of readily available P, moderately available Ca-P compounds, as well as mostly unavailable Al-P compounds. Bray-Kurtz P1 (pH = 3.2) should extract the readily available pool of soil P and Ca-P compounds, while not detecting the Al-P compounds extracted by Mehlich III. Distilled water (pH = 7.0) was the weakest extractant used and should only extract the readily available forms of soil P.

Differences among soil extractants were evaluated to provide an indication of the form of P that existed as a result of different application methods. Subtracting water extractable P from Bray-Kurtz P1 extractable P should provide an estimate of soil P that exists in Ca-P compounds, which have the potential to become plant available with time. Plots receiving P banded alone had a smaller difference between Bray extractable and water extractable P ($p<0.05$; Table 4). This analysis suggested that the difference in soil test P found to exist between dual-band applied P and gypsum and P banded alone was likely in the Ca-P form. This also supports the hypothesis that inclusion of gypsum in the band with P induced precipitation of Ca-P that did not occur when P was banded alone.

The second residual harvest in 1998 resulted in no differences among any treatments for forage or grain yield. Although the 1997 soil test results indicated that P levels were at least 50% sufficient for wheat production, soil NO_3-N and pH had become extremely limiting (5.6 kg ha^{-1} and 4.6, respectively). Therefore, it was not surprising that no response to residual P was observed in 1998.

CONCLUSIONS

Winter wheat forage and grain yield increased as a result of P fertilization (banded and broadcast) in each year of the study except 1995 when a severe drought resulted in no differences in grain yield. In 1996, the third year of the study, dual-band applications of P and gypsum resulted in increased forage and grain yields compared to P banded with no gypsum or P banded and gypsum broadcast. It is possible that dissociation of the gypsum may have induced precipitation of DCP and DCPD by saturating the soil solution with Ca^{2+}. This could have reduced the amount of applied P fixed as unavailable Fe or Al hydroxides. The DCP and DCPD could have slowly become plant available, thus explaining the increases in yield due to the dual-band in the third year of the study. A similar yield increase was observed when P and gypsum were both broadcast. This suggests that P and gypsum placed together, either in a band or on the soil surface, can form P compounds that slowly become plant available.

Reduced forage and grain yields were observed in the first two years of the study when N and P were dual-banded. This reduction was eliminated when gypsum was included in the band.

Residual grain yield increases as a result of the dual P-gypsum band compared to P banded without gypsum were observed in 1997, even though no fertilizer had been applied since the fall of 1995. By inducing precipitation of applied P as initially unavailable forms, a dual P-gypsum band application can increase long-term P availability for winter wheat forage and grain production on acid soils.

REFERENCES

Bray, R.H. and L.T. Kurtz. 1945. Determination of total, organic, and available forms of phosphorus in soils. Soil Sci. 59:39-45.

Large, E.C. 1954. Growth stages in cereals. Plant Pathol. 3:128-129.

Lindsay, W.L. 1979. Chemical equilibria in Soils. John Wiley & Sons, New York.

Mehlich, A. 1984. Mehlich no.3 extractant: A modification of Mehlich no. 2 extractant. Commun. Soil Sci. Plant Anal. 15:1409-1416.

Norton, S.L., W.E. Thomason, S.B. Phillips, S.E. Taylor, and W.R. Raun. 1995. Modification of a self propelled rotary mower for bermudagrass, alfalfa, and wheat forage harvest. *In* Agronomy abstracts. ASA, Madison, WI.

Olsen, S.R. and L.E. Sommers. 1982. Phosphorus. p. 403-430. *In* C.A. Black et al. (ed) Methods of soil chemical analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Racz, G.J., and R.J. Soper. 1967. Reaction products of orthophosphates in soils containing varying amounts of calcium and magnesium. Can. J. Soil Sci. 47:223-230.

Raun, W.R., and H.J. Barreto. 1991. Maize yield response as affected by phosphorus, sulfur and nitrogen as banded applications on a volcanic ash derived tropical soil. Commun. Soil Sci. Plant Anal. 22:1661-1676.

SAS Institute. 1990. SAS/STAT user's guide. Release 6.03 ed. SAS Inst., Cary, NC.

Savant, N.K., and G.J. Racz. 1973. Reaction products of applied pyrophosphates in some manitoba soils. Can. J. Soil Sci. 53:111-117.

Subbarao, Y.V., and, R. Ellis, Jr. 1975. Reaction products of polyphosphates and orthophosphates with soils and influence on uptake of phosphorus by plants. Soil Sci. Soc. Amer. Proc. 39:1085-1088.

Watanabe, F.S. and S.R. Olsen. 1965. Test of an ascorbic acid method for determining phosphorus in water and $NaHCO_3$ extracts from soil. Soil Sci. Soc. Am. Proc. 29:677-678.

Table 1. Initial soil test characteristics for Haskell, OK, 1993.

Organic C	Total N	NH_4-N	NO_3-N	P	K	pH
---------- g kg^{-1} --------		------------ mg kg^{-1} -----------				
7.9	0.4	24.9	11.2	18.1	164	5.4

Organic C, Total N - dry combustion; NH_4-N, NO_3-N - 2M KCl extract; P, K - Mehlich III; pH - 1:1 soil-water

Table 2. Treatment structure employed at Haskell, OK, 1993 to 1998.

Treatment	P rate	Gypsum rate	Method of Application‡	
	---kg P ha^{-1}---	---kg S ha^{-1}---	---P---	---S---
1	29	0	BWS	---
2	58	0	BWS	---
3	29	22	BWS	BWS
4	58	22	BWS	BWS
5	29	44	BWS	BWS
6	58	44	BWS	BWS
7	29	22	BWS	BC
8	58	22	BWS	BC
9	29	22	BC	BC
10	58	22	BC	BC
11	0	0	---	---
12	0	22	---	BWS
13	0	44	---	BWS
14	29†	44	BWS	BC
15	29†	22	BWS	BWS
16	29†	44	BWS	BWS

BWS - Banded with the seed, BC – Broadcast applied
All P applied as TSP (0-46-0) except †
† - P applied as DAP (18-46-0)

Table 3. Winter wheat forage and grain yield response to applied P and gypsum at Haskell, OK, 1994, 1995, and 1996.

Method§		P†	S‡	1994 Forage	1994 Grain	1995 Forage	1995 Grain	1996 Forage	1996 Grain
--P--	--S--	--- kg ha^{-1} ---		---------- kg ha^{-1} ----------					
----	BWS	0	22	2158	1424	1265	772	179	614
BWS	----	29	0	4802	2033	2433	1112	1084	2555
BWS	BWS	29	22	4594	2162	2446	1070	1746	2859
BWS	BC	29	22	4802	2192	2300	1137	1002	2621
BC	BC	29	22	3598	1552	1646	922	1571	2353
BWS	----	58	0	6048	2241	2767	547	1510	2591
BWS	BWS	58	22	5317	2162	2819	714	1494	2800
BWS	BC	58	22	5420	2006	2905	881	1685	2606
BC	BC	58	22	4584	2109	2477	1001	1892	2822
BWS	BWS	29	44	5046	2181	2664	1152	1565	2572
BWS	BWS	29¶	44	5348	2270	2224	1113	1184	2331
BWS	BC	29¶	44	4026	1978	1252	762	987	2538
SED				413	162	395	160	226	192

† - applied as TSP (0-46-0) unless denoted otherwise; ‡ - applied as gypsum (17% S); § - BWS – band applied, BC - broadcast applied; ¶ - applied as DAP (18-46-0); SED – standard error of the difference between two equally replicated means

Table 4. Residual soil test P as determined from composite surface samples (0 to 15-cm deep) collected within 2.5 cm of the P or dual-applied P and gypsum bands, 1997.

P	S as gypsum	Mehlich III	Bray-Kurtz P1	DI Water	Bray-Water†
----- kg ha^{-1} -----		---------------------------- kg P ha^{-1}	-------------------------		
0	0	19.4	13.9	4.1	9.8
29	0	30.4	23.9	5.1	18.9
29	22	54.5	44.7	7.2	37.4
29	44	53.1	40.1	6.7	33.4
58	0	71.1	60.1	7.8	52.3
58	22	76.8	58.9	8.3	50.6
58	44	71.4	56.7	7.5	49.2
SED		5.2	4.4	0.4	4.0

† - Bray extractable soil P minus distilled water extractable soil P; DI – deionized;
SED – standard error of the difference between two equally replicated means

VITA

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Candidate for the Degree of

Doctor of Philosophy

Thesis: I. ALFALFA YIELD RESPONSE TO METHOD AND TIMING OF APPLIED PHOSPHORUS

II. EFFECT OF DUAL APPLIED PHOSPHORUS AND GYPSUM ON WHEAT FORAGE AND GRAIN YIELD

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