

## PHOSPHORUS AND MICRONUTRIENT AVAILABILITY FROM DUAL APPLICATION OF NITROGEN AND PHOSPHORUS USING LIQUID FERTILIZERS<sup>1</sup>

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Applications of ammoniacal forms of N along with P in the same injection zone can enhance P availability relative to applications of P alone. The spatial and temporal variability of available P was assessed in acid soil and in alkaline soil, using ammonium polyphosphate (APP) as a P source and urea ammonium nitrate (UAN) as a N source. Either ammonium polyphosphate or APP+UAN, at a constant P application rate, was injected into soil-filled boxes using an apparatus that allowed a needle to be pulled through the soil below the surface, simulating subsurface band application. Soils boxes were sampled by sequentially removing concentric cylindrical cores of increasing radii centered around the line of fertilizer injection. Sampling times were 1, 4, 12, 24, and 36 weeks. Available P was determined by either the Bray-1 or the Olsen procedure. Available Zn, Fe, Cu, and Mn were also determined with the DTPA procedure. For both soils, soil pH generally decreased in the first 12 weeks and then increased during the remaining incubation period. Treatment comparisons within rings over time showed that APP+UAN generally gave significantly higher extractable P when compared with the APP treatment. Total available P, calculated as the sum of the products of soil dry mass and extractable P for each ring, was significantly higher for APP+UAN compared with APP at all sampling times. The decline in total available P with time was best described by  $y = a(e^{-bt} + c)$ , where  $y$  is the total available P (mg) at time  $t$  (weeks) and  $a$ ,  $b$ , and  $c$  are curve-fitting parameters. The value of  $b$  was greater for the APP treatment for both soils, indicating that total available P declined faster for this treatment than for the APP+UAN treatment. Treatment effects on DTPA-extractable Fe and Mn generally

corresponded to changes in soil pH with concentrations increasing with decreasing pH. For DTPA-extractable Zn and Cu, however, concentrations were often lower for the treatment with the lowest pH.

Methods of fertilizer application that can increase P fertilizer use efficiency are of interest for economic and environmental reasons. Placement of N and P fertilizers in the same retention zone, referred to as dual N and P application, has been reported to improve availability and recovery of fertilizer P and to increase crop yields under P-deficient conditions (Leikam et al. 1983). Dual application of N and P consists of subsurface injection of predominantly  $\text{NH}_4^+$ -N and P fertilizers in the same retention zone of the soil (Hanson and Westfall 1985; Leikam et al. 1983). Several mechanisms have been suggested as contributing factors for the N-P interaction. These include enhanced root growth in the fertilized zone (Grunes et al. 1958),  $\text{NH}_4^+$ -enhancement of P uptake by roots (Miller and Ohlrogge 1958), rhizocylinder acidification caused by  $\text{NH}_4^+$ -N (Kirkby and Mengel, 1967), increased  $\text{H}_2\text{PO}_4^-/\text{HPO}_4^{2-}$  ratios in the soil solution (Miller et al. 1970), and increased solubility of fertilizer reaction products in the soil (Hanson and Westfall 1985, 1986). This study will focus on fertilizer reaction products.

Hanson and Westfall (1985, 1986) demonstrated that Bray- and  $\text{NaHCO}_3$ -extractable P generally increased when P was applied with  $\text{NH}_4\text{OH}$  compared with P applied alone. Solubility measurements in acid and neutral soils suggested that the initial high pH immediately after dual application allowed the formation of highly available Ca-P reaction products, which then dissolved as the pH of the fertilized zone decreased as a result of nitrification. In these soils, the  $\text{NH}_4^+$ -N fertilizer had to be an alkaline agent for the increased P solubility to occur (Hanson and Westfall 1985). Experiments with a calcareous soil implied that any  $\text{NH}_4^+$ -N fertilizer would induce higher P availability when dually applied with P, because of the acidifying

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effect of nitrification (Hanson and Westfall 1986).

Field studies conducted in Kansas by Leikam et al. (1983) showed significant advantages resulting from preplant dual application, using UAN or anhydrous  $\text{NH}_3$  with APP, on yield and P uptake for wheat (*Triticum aestivum* L.) grown on low P soils compared with P application alone. Fixen and Wolkolwski (1981) compared dual N-P placement of anhydrous  $\text{NH}_3$  and APP with a conventional band placement of N and P for corn (*Zea Mays* L.) and found little advantage for the dual application over the conventionally used N-P starter. Grant (1986), using winter wheat, and Raun et al. (1987), using corn, showed dual N-P application increased P uptake and grain yield more than when P alone was banded to the side or below the seed. Harms (1988) obtained an average increase in wheat yields of 5.6% from dual injected P fertilizer with  $\text{NH}_3$  compared with P alone on a high P soil. Mortvedt and Kelsoe (1988) measured levels of extractable P with time and distance from an APP band. Phosphorus diffused about 2 cm from the fertilizer band after 7 days and continued to diffuse with time. However, the authors did not assess dual application.

Phosphorus-micronutrient interactions have generally been recognized as detrimental to plant growth and have been termed "P-induced micronutrient deficiency." High P availability can induce micronutrient deficiencies in soils with low micronutrient availabilities and tends to depress yields and induce low P use efficiency (Wallace et al. 1978; Murphy et al. 1981; Mortvedt and Kelsoe 1990). According to Murphy et al. (1981), the effect of P on micronutrients depends on factors such as the form and placement of P and soil pH. Band application of P depressed Zn availability more than broadcast P. Murphy et al. (1981) and Mortvedt and Kelsoe (1990) demonstrated an inverse relationship between pH and micronutrient solubilization. They showed that hydrolysis of urea increased soil pH soon after application and, in this high pH area, diethylenetriaminepentaacetic acid (DTPA)-extractable micronutrient levels were low. The influence of dual applied N and P on micronutrient availability has not been widely studied.

The P fertilizers used for dual application are fluid ammonium polyphosphates (APP). They can be applied with anhydrous ammonia using

separate delivery tubes or mixed with N solutions in one tank before application (Kissel and Whitney 1979). Most laboratory studies of dual applied N and P have used  $\text{NH}_4\text{OH}$  as a substitute for  $\text{NH}_3$ . Other N sources, such as UAN, have not been intensively investigated, particularly in detailed laboratory studies. Urea ammonium nitrate is a nonpressure N solution and presents some advantages that may justify its use in dual application. Urea ammonium nitrate solution is easy to band apply and combines with other liquid fertilizers, such as APP. Moreover, UAN is an alkalizing agent that can raise soil pH after application as a result of hydrolysis of urea.

Most studies of dual N and P application have assessed changes in available P over short periods of time and not with distance. Therefore, objectives of this research are to assess spatial and temporal variability of soil pH, extractable P, and extractable micronutrients from band applications of APP alone and in combination with UAN.

#### MATERIALS AND METHODS

Two soils with different chemical and physical properties were used in laboratory experiments. Soil samples were collected from the surface horizons (0–15 cm) of areas mapped as a Woodson silt loam (Thermic Abruptic Argiaquolls) and a Harney silt loam (Mesic Typic Argiustolls). Samples were sieved, homogenized, air-dried, and stored at room temperature. Selected physical and chemical properties are given in Table 1. Particle size analysis of representative soil samples was done using the method described by Whittig and Allardice (1986). Carbon was determined by dry combustion (Leco Induction Furnace) as developed by Allison (1965).

Soil was packed in polyethylene boxes 13.2 cm wide by 13.2 cm long by 8 cm deep at a bulk density of 1.2 g/cm<sup>3</sup>. The boxes were similar to those used by Stehouwer and Johnson (1989). Before it was packed, the soil was moistened to 20% gravimetric moisture content using a spray bottle. A mass of soil equivalent to 1-cm depth was added to the box with careful tamping between soil additions to obtain uniform density throughout the box. A stainless steel needle was placed across the box before filling through two holes located in the middle of the bottom wall of the box and the cover. One side of the boxes was open, simulating the soil surface.

TABLE 1  
Selected chemical and physical properties of the soil samples

Soil Series	Sand	Silt	Clay	pH	C	Extractable P	Zn	DTPA-extractable		Mn
								Fe	Cu	
		%			g/kg		mg/kg			
Woodson	6	61	33	5.8	42	10.4 <sup>a</sup>	4.8	82.0	6.6	42.0
Harney	17	58	25	7.9	26	7 <sup>b</sup>	2.4	7.0	0.9	7.9

<sup>a</sup> Bray extraction.

<sup>b</sup> NaHCO<sub>3</sub> extraction.

Treatments were applied with an apparatus developed by Izaurralde et al. (1986). This application system, which allows band injection of liquid fertilizer in the soil, consists of a movable platform that allows an injection needle to be pulled through the soil at a constant speed, simulating band injection by a tractor-drawn field applicator. A syringe acts as a reservoir for fluid fertilizers, and the plunger of the syringe is attached to the platform such that a uniform flow rate is produced as the platform moves. A polyethylene tube connects the syringe to the needle. The fertilizer injection system was calibrated to obtain desired fertilizer delivery rates. Precise application rates were obtained through control of the liquid fertilizer delivery rates to injectors and speed of the platform. The needle was held stationary with a clamp on a ringstand while the box moved with the platform.

The P source was liquid APP (10-15-0) and the N source was UAN (28-0-0). The treatments were APP alone or combined with UAN. The APP+UAN and APP treatments supplied 51 and 26 kg N/ha, respectively. Phosphorus was applied at 40 kg P/ha. To calculate the mass of N and P per ha, a knife spacing of 76 cm was used. Dual application was made by mixing UAN and APP and injecting the mixture. Fertilized soils were stored in an incubator at 25°C. Soils were sampled at 1, 4, 12, 24, and 36 weeks after fertilizer application. The sampling method was an adaptation of the method developed by Izaurralde et al (1986) and consisted of replacing the original cover of the box with a set of covers with circular holes of increasing radii. Concentric rings of soil were then removed by driving a series of metal cylinders (each with its own template to center the cylinders around the line of injection) with radii of 1.25, 2.5, 3.5, 5.0, and 6.5 cm, referred to as ring 1, 2, 3, 4, and 5, respectively. The rings were inserted and removed one at a time, beginning with the center

(the smallest ring). After removal of each ring, soil was air-dried, ground, mixed, and stored in plastic bags at 4°C until analyses. Sampling was destructive; therefore, each treatment was applied to 15 boxes per soil to allow five sampling times with three replications.

Soil pH was measured using a 1:1 soil/water ratio. Available P was determined by the Bray-1 P (0.03 M NH<sub>4</sub>F + 0.025 M HCl) test as developed by Bray and Kurtz (1945) in the Woodson soil and by the Olsen P (0.5 M NaHCO<sub>3</sub>) soil test as described by Olsen and Sommers (1982) in the Harney soil. Phosphorus concentrations in extracts were determined with the Murphy and Riley (1962) procedure. Samples taken at 4 weeks were extracted with the DTPA procedure described by Lindsay and Norvell (1978). Iron, Zn, Mn, and Cu were determined in the extracts with atomic absorption spectrophotometry. Micronutrient concentrations in the APP and the UAN are given in Table 2.

One-way ANOVA procedure was used to compare P availability among treatments at 0.05 level of significance. Nonlinear regressions were done with the NLIN procedure in SAS (Barr et al. 1976). Analysis of variance were done for 2-way and 3-way interactions between treatment, time, and ring for all variables.

## RESULTS AND DISCUSSION

The analysis of variance indicated that the 2-way and 3-way interactions were significant for all variables except for pH in the Woodson soil. Therefore, individual treatment means are presented exclusively.

### Soil pH and NH<sub>4</sub><sup>+</sup> concentrations

After 1 week, pH increased relative to the initial soil pH of 5.8 in ring 1 for both treatments and for the APP+UAN treatment in ring 2 for the Woodson soil (Table 3). The changes in pH

for both treatments at 1 week may be partly due to the pH of the fertilizers. The initial pH of the APP and the APP+UAN solutions was 6.5 and 6.1, respectively. The higher pH at week 1 for the dual treatment compared with the APP treatment may be attributed to urea hydrolysis in the UAN. Soil pH was not influenced by the two treatments in rings 3 and 5 at 1 week.

Soil pH in ring 1 was significantly lower at 4 weeks than at 1 week and was likely caused by nitrification (Table 3). Ammonium levels showed the greatest relative decrease from 1 to 4 weeks of incubation under both treatments (data not shown), corresponding to the greatest decline in pH. The decline in pH in ring 1 was greater for the dual treatment than for APP and was related to greater acidification with APP+UAN than with APP treatment because of higher amounts of  $\text{NH}_4\text{-N}$  available for nitrification. There were no significant differences in pH among treatments at 4 weeks in rings 1 and 2. Soil pH was significantly higher with APP than with APP+UAN in rings 3, 4, and 5

at 4 weeks. The lowest pH over all rings and time occurred with the dual application in ring 3 at 4 and 12 weeks. Twelve to 36 weeks after fertilization, soil pH remained relatively constant in all rings.

After 1 week of incubation, pH in the Harney soil was lower than the initial pH of 7.9 for both treatments in ring 1 (Table 4), but no significant differences in pH were observed between treatments. This may be primarily due to the pH of the fertilizer solutions and nitrification. Soil pH for the remaining rings was significantly lower with the APP+UAN treatment compared with APP alone. Soil pH continued to decrease through 4-weeks in all rings, again because of nitrification of  $\text{NH}_4^+$ . There were no significant differences in soil pH among treatments in rings 1, 4, and 5; however, soil pH was significantly lower for APP+UAN than for the APP treatment in rings 2 and 3. Soil pH increased in all rings after 12 weeks, with the APP treatment generally being higher than the dual treatment. The increase in soil pH can be associated with the neutralizing effect of the  $\text{CaCO}_3$  in the soil. Soil pH remained at 7.4 or higher in rings 3, 4, and 5 throughout the experiment; however, at the end of 36 weeks, soil pH returned to its initial value with both treatments.

#### Extractable P

Throughout the incubation period, the highest levels of extractable P in the Woodson soil were

TABLE 2  
Micronutrient concentrations in the fertilizers used

Fertilizer	Zn	Fe	Cu	Mn
	mg/kg			
APP (10-34-0)	249	4800	1.2	107
UAN (28-0-0)	1.3	16	nd <sup>a</sup>	0.9

<sup>a</sup> nd = nondetectable.

TABLE 3  
The effects of treatments, time, and distance from the fertilizer injection line on pH for the Woodson soil

Treatment	Sampling times (weeks)				
	1	4	12	24	36
<i>Ring 1</i>					
APP	6.2 <sup>b*</sup>	5.7 <sup>c</sup>	5.7 <sup>cd</sup>	5.5 <sup>cde</sup>	5.6 <sup>cde</sup>
APP+UAN	6.6 <sup>a</sup>	5.6 <sup>cd</sup>	5.4 <sup>de</sup>	5.4 <sup>de</sup>	5.5 <sup>cde</sup>
<i>Ring 2</i>					
APP	5.7 <sup>b</sup>	5.1 <sup>de</sup>	5.2 <sup>cd</sup>	5.1 <sup>cd</sup>	5.2 <sup>cd</sup>
APP+UAN	6.2 <sup>a</sup>	5.1 <sup>de</sup>	4.9 <sup>e</sup>	5.3 <sup>c</sup>	5.0 <sup>de</sup>
<i>Ring 3</i>					
APP	5.7 <sup>a</sup>	5.2 <sup>bc</sup>	5.2 <sup>bc</sup>	5.3 <sup>b</sup>	5.3 <sup>b</sup>
APP+UAN	5.6 <sup>a</sup>	4.8 <sup>e</sup>	4.8 <sup>e</sup>	5.1 <sup>cd</sup>	4.9 <sup>de</sup>
<i>Ring 4</i>					
APP	5.7 <sup>a</sup>	5.6 <sup>b</sup>	5.4 <sup>d</sup>	5.4 <sup>cd</sup>	5.4 <sup>cd</sup>
APP+UAN	5.6 <sup>bc</sup>	5.1 <sup>ef</sup>	5.0 <sup>f</sup>	5.2 <sup>e</sup>	5.1 <sup>ef</sup>
<i>Ring 5</i>					
APP	5.7 <sup>a</sup>	5.7 <sup>a</sup>	5.6 <sup>a</sup>	5.5 <sup>a</sup>	5.5 <sup>ab</sup>
APP+UAN	5.6 <sup>a</sup>	5.4 <sup>bc</sup>	5.3 <sup>c</sup>	5.3 <sup>c</sup>	5.2 <sup>c</sup>

\* Means with the same letter within ring are not significantly different at the 0.05 level of significance.

TABLE 4

*The effects of treatments, time, and distance from the fertilizer injection line on soil pH for the Harney soil*

Treatment	Sampling times (weeks)				
	1	4	12	24	36
	<i>Ring 1</i>				
APP	7.3 <sup>abc*</sup>	6.8 <sup>d</sup>	7.3 <sup>bc</sup>	7.4 <sup>abc</sup>	7.6 <sup>a</sup>
APP+UAN	7.4 <sup>abc</sup>	7.0 <sup>d</sup>	7.3 <sup>c</sup>	7.5 <sup>ab</sup>	7.5 <sup>ab</sup>
	<i>Ring 2</i>				
APP	7.8 <sup>b</sup>	7.4 <sup>d</sup>	7.7 <sup>bc</sup>	7.8 <sup>b</sup>	8.0 <sup>a</sup>
APP+UAN	7.6 <sup>cd</sup>	7.2 <sup>e</sup>	7.7 <sup>bc</sup>	7.7 <sup>bc</sup>	7.9 <sup>b</sup>
	<i>Ring 3</i>				
APP	8.0 <sup>a</sup>	7.6 <sup>d</sup>	7.8 <sup>bc</sup>	7.9 <sup>b</sup>	8.1 <sup>a</sup>
APP+UAN	7.5 <sup>d</sup>	7.4 <sup>e</sup>	7.7 <sup>c</sup>	7.8 <sup>c</sup>	7.9 <sup>b</sup>
	<i>Ring 4</i>				
APP	8.1 <sup>a</sup>	7.7 <sup>cd</sup>	7.9 <sup>b</sup>	7.9 <sup>b</sup>	8.1 <sup>a</sup>
APP+UAN	7.5 <sup>cd</sup>	7.5 <sup>c</sup>	7.6 <sup>de</sup>	7.7 <sup>cd</sup>	7.9 <sup>bc</sup>
	<i>Ring 5</i>				
APP	8.2 <sup>a</sup>	7.7 <sup>cd</sup>	7.7 <sup>cd</sup>	7.8 <sup>c</sup>	7.9 <sup>b</sup>
APP+UAN	7.8 <sup>c</sup>	7.6 <sup>d</sup>	7.6 <sup>d</sup>	7.7 <sup>cd</sup>	7.8 <sup>bc</sup>

\* Means with the same letter within ring are not significantly different at the 0.05 level of significance.

observed in ring 1 (Table 5). Extractable P with APP+UAN was always greater than APP alone at all sampling times in ring 1. For the remaining rings, extractable P was also higher in the dual treatment compared with the APP treatment, but differences were not always significant. These results were similar to those of Hanson and Westfall (1985), who compared NH<sub>4</sub>OH+APP to APP alone in acid and neutral soils. Enhanced extractable P with the dual treatment may be due to the presence of soluble P reaction products formed from the dissolution of the initial reaction products as the soil pH decreased because of nitrification of the fertilizer NH<sub>4</sub><sup>+</sup>. The APP+UAN treatment increases the pH immediately after application to a value higher than that for APP as a result of the addition of the UAN. Our data indicate that the increased extractable P with APP+UAN occurs 3.5 cm from the line of injection. These data also support the observations of Leikam et al. (1983), in which dual applications of UAN and APP increased P availability.

Extractable P increased in rings 2 and 3 during the first 4 and 12 weeks, respectively, and then decreased. The increase in P was probably caused by diffusion of P from ring 1 into rings 2 and 3. The increase in P levels was not observed for the APP+UAN and APP treatments in rings 4 and 5. Moreover, both treatments resulted in only slightly higher P concentrations than the initial P soil test (10.4 mg/kg), indicat-

ing little movement of the fertilizer solutions into the outer rings. The average Bray-1 level in ring 5 throughout the incubation period was 12 mg/kg for APP treatment and 15 mg/kg for the APP+UAN treatment.

Olsen-extractable P concentrations in the Harney soil were highest in ring 1 throughout the incubation period, whereas P concentrations with APP+UAN were significantly higher than with APP alone (Table 6). Similar results were observed in the Woodson soil and by Hanson and Westfall (1986), who reported greater available P levels with NH<sub>4</sub>OH+APP compared with APP alone in an alkaline soil. Extractable P decreased throughout the incubation in ring 2, although P levels were significantly higher with APP+UAN than with APP alone through 24 weeks of incubation. In ring 3, available P increased during the first 4 weeks and decreased thereafter. Extractable P in rings 4 and 5 was not influenced by the treatments until the last sampling time, when a slight increase was observed. Treatment effects on extractable P were not observed in the outer two rings.

In both soils, extractable P concentrations decreased with distance from ring 1 with both treatments throughout the incubation. These results are comparable to those of Mortvedt and Kelsoe (1988), who assessed changes in available P with distance from APP applied at a rate of 18 kg P/ha. After only 7 days, however, they observed a decrease in available P in the fertil-

TABLE 5

The effects of treatments, time, and distance from the fertilizer injection line on extractable Bray P concentrations for the Woodson soil

Treatment	Sampling times (weeks)				
	1	4	12	24	36
	<i>mg P/kg</i>				
	<i>Ring 1</i>				
APP	1087 <sup>b*</sup>	589 <sup>d</sup>	466 <sup>e</sup>	365 <sup>f</sup>	268 <sup>g</sup>
APP+UAN	1322 <sup>a</sup>	1088 <sup>b</sup>	911 <sup>c</sup>	604 <sup>d</sup>	302 <sup>f</sup>
	<i>Ring 2</i>				
APP	229 <sup>bc</sup>	258 <sup>ab</sup>	220 <sup>b</sup>	160 <sup>cd</sup>	113 <sup>d</sup>
APP+UAN	269 <sup>ab</sup>	336 <sup>a</sup>	249 <sup>b</sup>	233 <sup>bc</sup>	148 <sup>cd</sup>
	<i>Ring 3</i>				
APP	14 <sup>g</sup>	18 <sup>f</sup>	25 <sup>c</sup>	20 <sup>e</sup>	21 <sup>e</sup>
APP+UAN	18 <sup>f</sup>	30 <sup>a</sup>	31 <sup>a</sup>	24 <sup>d</sup>	24 <sup>b</sup>
	<i>Ring 4</i>				
APP	14 <sup>ab</sup>	13 <sup>bc</sup>	14 <sup>ab</sup>	13 <sup>b</sup>	11 <sup>c</sup>
APP+UAN	15 <sup>ab</sup>	15 <sup>a</sup>	14 <sup>ab</sup>	15 <sup>ab</sup>	10 <sup>c</sup>
	<i>Ring 5</i>				
APP	12 <sup>e</sup>	14 <sup>bc</sup>	12 <sup>e</sup>	13 <sup>cd</sup>	12 <sup>de</sup>
APP+UAN	15 <sup>ab</sup>	15.4 <sup>a</sup>	12 <sup>e</sup>	12.3 <sup>de</sup>	9 <sup>f</sup>

\* Means with the same letter within ring are not significantly different at the 0.05 level of significance.

TABLE 6

The effects of treatments, time, and distance from the fertilizer injection line on extractable Olsen-P concentrations for the Harney soil

Treatment	Sampling times (weeks)				
	1	4	12	24	36
	<i>mg P/kg</i>				
	<i>Ring 1</i>				
APP	413 <sup>b*</sup>	250 <sup>c</sup>	174 <sup>f</sup>	189 <sup>ef</sup>	138 <sup>g</sup>
APP+UAN	569 <sup>a</sup>	390 <sup>b</sup>	220 <sup>d</sup>	212 <sup>de</sup>	191 <sup>ef</sup>
	<i>Ring 2</i>				
APP	141 <sup>b</sup>	102 <sup>c</sup>	87 <sup>d</sup>	56 <sup>f</sup>	44 <sup>g</sup>
APP+UAN	181 <sup>a</sup>	145 <sup>b</sup>	99 <sup>c</sup>	75 <sup>e</sup>	47 <sup>g</sup>
	<i>Ring 3</i>				
APP	20.3 <sup>c</sup>	29 <sup>a</sup>	9.6 <sup>f</sup>	7.1 <sup>g</sup>	17.1 <sup>d</sup>
APP+UAN	18.0 <sup>d</sup>	30 <sup>a</sup>	15.1 <sup>e</sup>	10.1 <sup>f</sup>	22.2 <sup>b</sup>
	<i>Ring 4</i>				
APP	18.4 <sup>b</sup>	9.6 <sup>de</sup>	9.2 <sup>de</sup>	7.1 <sup>f</sup>	15.8 <sup>c</sup>
APP+UAN	11.0 <sup>d</sup>	21.2 <sup>a</sup>	9.5 <sup>de</sup>	8.5 <sup>ef</sup>	15.7 <sup>c</sup>
	<i>Ring 5</i>				
APP	10.8 <sup>bc</sup>	6.7 <sup>e</sup>	8.1 <sup>de</sup>	8.0 <sup>de</sup>	14.8 <sup>a</sup>
APP+UAN	12.0 <sup>b</sup>	12.3 <sup>b</sup>	10.0 <sup>cd</sup>	8.5 <sup>de</sup>	14.7 <sup>a</sup>

\* Means with the same letter within ring are not significantly different at the 0.05 level of significance.

izer band, whereas at 2.5 cm from the band, available P concentrations had decreased to that of the untreated soil. In this study, Olsen P decreased from 590 mg/kg in the fertilizer band to 130 mg/kg at 2.5 cm from the band, a reduction of 88%. Kitchen et al. (1990) reported that residual P fertilizer could not be detected beyond 6 cm from P bands after 12 to 23 months under field conditions.

Calculation of the distance P could diffuse in the incubation time is difficult for a variety of reasons. Initially, the chemical and physical environment of the injection line is dominated by the fertilizer solutions themselves. The effective diffusion coefficient ( $D_e$ ) would also vary with distance from the injection line because  $D_e$  is proportional to the inverse of the differential buffer capacity, which varies with P additions

(Barber 1980). In addition, an increase in extractable P is not an accurate indicator of P movement. However, Crank (1975) developed an equation for diffusion from a line source of given mass per length that predicts, using a realistic range of  $D_e$  values ( $1.1 \times 10^{-11}$  to  $1.1 \times 10^{-7}$   $\text{cm}^2/\text{s}$ ), that P could move from 0.12 to 6.8 cm in 282 days, which is in agreement with the observed data.

Throughout the incubation, comparisons of treatments within rings showed that available P concentrations with APP+UAN were always higher than with APP alone in ring 1 and often in ring 2, whereas few differences were observed in the outer rings. These results lead to the conclusion that dual N-P application produces higher available P concentrations in a narrow zone around the P injection band and that, as the distance from the zone increases, no significant differences occur between the two treatments.

#### Total available P

Total available P in each box at each sampling time represented the sum of the products of dry soil mass and available P for each ring. Available P in rings was summed to reflect the influence of treatments on the total soil influenced by the P applications, rather than treatment effects on individual rings. The decline in available P with time is described by the model:

$$y = a(e^{-bt} + c) \quad (1)$$

although other models were considered (e.g.,  $y = a e^{-bt}$  and  $y = a(e^{-bt} + 1)$ ), where  $y$  is the total available P (mg) at time  $t$  (weeks), and  $a$ ,  $b$ , and  $c$  are curve fitting parameters. These models are comparable to the ones developed by Cox et al. (1981) and Kitchen et al. (1990) in that the decline in available P with time is described by an exponential equation. Equation (1) provided the best fit for the data based on the highest regression coefficient values and the lowest residual mean square (Figs. 1 and 2).

For both soils, total available P was significantly higher with APP+UAN, compared with APP alone, throughout the incubation (Figs. 1 and 2). In addition, the parameter  $b$ , which influences the curvature of the function at low values of  $t$ , was greater for the APP treatment than for APP+UAN treatment, which indicates that available P declined more rapidly for the former treatment than for the latter. This is more pronounced with the Harney soil. Direct

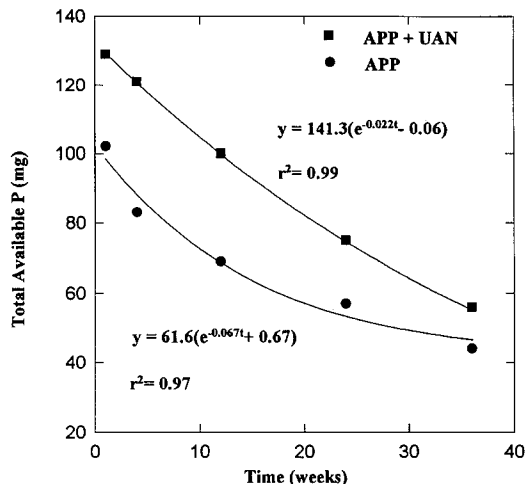


FIG. 1. Total available P as a function of time for the Woodson soil.

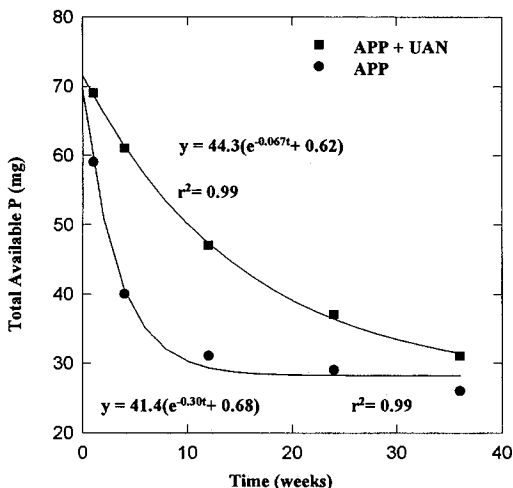


FIG. 2. Total available P as a function of time for the Harney soil.

comparisons between the general shapes of the curves between soils cannot be made because different extractants were used to assess available P. The curves do suggest, however, that dual application was relatively more effective in increasing P availability in the Harney soil than in the Woodson soil.

Previous studies of reaction product chemistry from dual applied N and P have only been conducted for 90 days or less (Hanson and Westfall 1985, 1986). After 282 days of incubation in this study, available P was still significantly higher for the APP+UAN compared with APP,

which suggests that the residual value of dual applied P may be higher, although this needs to be evaluated over longer periods of time and under field conditions.

The need to evaluate residual P in bands has been noted by many authors (Kitchen et al. 1990; Havlin et al. 1992; Halvorson 1992). The primary application of the information would be an improvement of P recommendation models used for reduced or no-till cropping systems. Knowledge of the available P concentration in the band is essential for developing fertilizer P residue degradation models for use in P management.

#### *Extractable micronutrients*

DTPA-extractable Zn, Fe, Mn, and Cu were determined on samples collected after 1, 4, and 12 weeks of incubation. Only data from 4 weeks of incubation are presented because the lowest soil pH values occurred at this time with the Harney soil (Table 4), which would benefit the most from an enhancement of micronutrient availability because of the high soil pH.

For both soils, DTPA-extractable Zn, Mn, and Fe concentrations were highest in ring 1 and declined with distance from the band (Tables 7 and 8). These results are comparable to those of Mortvedt and Kelsoe (1987, 1988) who found significantly higher extractable Zn, Fe, and Mn levels within an APP band. Thirty-five days after an APP application, a decrease in extract-

able Fe from 79 mg/kg in the fertilizer band (0–0.5 cm) to 64 mg/kg at 2–2.5 cm from the band was observed. The relatively high levels of extractable Zn, Mn, and Fe may be related to their high concentrations in the APP. No such trend was evident with Cu because the Cu concentrations in the fertilizers were very low (Table 2).

The DTPA-extractable Zn concentration was significantly higher for the APP+UAN treatment compared with the APP treatment in ring 3 for the Woodson soil, whereas the opposite effect was found in ring 5 (Table 7). The extractable Fe concentration in ring 3 was significantly higher for the APP+UAN treatment than for the APP treatment, which may be attributable to the lower soil pH for the APP+UAN treatment (Table 3). A similar effect was observed for extractable Mn in rings 3 and 4.

Extractable Cu concentrations with the APP treatment were significantly higher than the dual treatments in rings 2 to 5 for the Woodson soil, with a similar trend in ring 1, although the difference is not statistically significant (Table 7). This result is the opposite of what was expected, based on the lower soil pH for the dual treatment (Table 3). A similar effect was found in rings 4 and 5 at 1 week and in all rings at 12 weeks (data not shown). The reason for these differences is not known. Generally, a metal-P interaction reduces the plant availability of the metal in the presence of high available P concentrations (Murphy et al. 1980), and the dual application generally maintains a higher avail-

TABLE 7

*The effects of treatments and distance from the fertilizer injection line on DTPA-extractable micronutrients at 4 weeks for the Woodson soil*

Treatment	Zn	Fe	Cu	Mn
	<i>mg/kg</i>			
	<i>Ring 1</i>			
APP	8.6 <sup>ab</sup>	97.0 <sup>a</sup>	5.1 <sup>a</sup>	41.7 <sup>a</sup>
APP+UAN	8.6 <sup>a</sup>	93.7 <sup>a</sup>	3.9 <sup>a</sup>	42.7 <sup>a</sup>
	<i>Ring 2</i>			
APP	5.8 <sup>b</sup>	88.7 <sup>a</sup>	5.8 <sup>a</sup>	38.0 <sup>a</sup>
APP+UAN	6.5 <sup>a</sup>	94.7 <sup>a</sup>	4.0 <sup>b</sup>	44.3 <sup>b</sup>
	<i>Ring 3</i>			
APP	5.6 <sup>a</sup>	80.3 <sup>b</sup>	5.7 <sup>a</sup>	38.7 <sup>b</sup>
APP+UAN	5.4 <sup>a</sup>	87.0 <sup>a</sup>	4.0 <sup>b</sup>	43.3 <sup>a</sup>
	<i>Ring 4</i>			
APP	5.4 <sup>a</sup>	73.0 <sup>a</sup>	5.0 <sup>a</sup>	27.7 <sup>b</sup>
APP+UAN	5.0 <sup>a</sup>	72.0 <sup>a</sup>	3.5 <sup>b</sup>	42.3 <sup>a</sup>
	<i>Ring 5</i>			
APP	6.0 <sup>a</sup>	74.3 <sup>a</sup>	5.1 <sup>a</sup>	31.7 <sup>a</sup>
APP+UAN	4.8 <sup>b</sup>	68.3 <sup>a</sup>	3.4 <sup>b</sup>	34.7 <sup>a</sup>

\* Means with the same letter within ring are not significantly different at the 0.05 level of significance.



TABLE 8

The effects of treatments and distance from the fertilizer injection line on DTPA-extractable micronutrients at 4 weeks for the Harney soil

Treatment	Zn	Fe	mg/kg	
			Cu	Mn
			<i>Ring 1</i>	
APP	3.1 <sup>a*</sup>	16.7 <sup>a</sup>	0.9 <sup>a</sup>	17.0 <sup>a</sup>
APP+UAN	2.4 <sup>b</sup>	13.7 <sup>b</sup>	0.7 <sup>b</sup>	13.3 <sup>b</sup>
			<i>Ring 2</i>	
APP	2.9 <sup>a</sup>	8.0 <sup>b</sup>	0.8 <sup>a</sup>	9.0 <sup>a</sup>
APP+UAN	2.0 <sup>b</sup>	10.3 <sup>a</sup>	0.7 <sup>a</sup>	8.7 <sup>a</sup>
			<i>Ring 3</i>	
APP	3.3 <sup>a</sup>	5.3 <sup>b</sup>	0.7 <sup>a</sup>	9.0 <sup>a</sup>
APP+UAN	1.8 <sup>b</sup>	6.7 <sup>a</sup>	0.6 <sup>b</sup>	7.3 <sup>a</sup>
			<i>Ring 4</i>	
APP	3.4 <sup>a</sup>	5.0 <sup>b</sup>	0.8 <sup>a</sup>	7.7 <sup>a</sup>
APP+UAN	1.8 <sup>b</sup>	6.0 <sup>a</sup>	0.7 <sup>a</sup>	7.0 <sup>a</sup>
			<i>Ring 5</i>	
APP	3.1 <sup>a</sup>	5.0 <sup>a</sup>	0.7 <sup>a</sup>	7.7 <sup>a</sup>
APP+UAN	2.0 <sup>b</sup>	5.7 <sup>a</sup>	0.6 <sup>b</sup>	7.0 <sup>a</sup>

\* Means with the same letter within ring are not significantly different at the 0.05 level of significance.

able P concentration than the APP treatment (Tables 5 and 6). Soil chemical changes from the metal-P interaction have not been conclusively shown, however (Adams 1980). It is also possible that increases in extractable Fe and Mn result in increased competition for DTPA in the extracting solution. Thus, the reductions in extractable Cu are the result of increased Fe and Mn availability.

The DTPA-extractable Zn, Cu, and Mn concentrations for the APP treatment were significantly higher than the dual treatment in ring 1 of the Harney soil, which may be due to the lower soil pH for the APP treatment (Tables 4 and 8). For the remaining rings, extractable Zn concentrations were significantly lower for the dual treatment than for the APP treatment despite the dual treatments having lower soil pH values. The same result was found for rings 2 to 5 at 1 week and all rings at 12 weeks (data not shown). Similar to Cu for the Woodson soil, the reason for this difference is not known. The DTPA-extractable Fe concentrations were significantly higher for the APP treatment in ring 1 and for the APP+UAN treatments in rings 2 to 4. In all cases, extractable Fe was higher for the treatment with the lowest soil pH.

#### SUMMARY AND CONCLUSIONS

Results confirm UAN, as an ammoniacal N fertilizer, can influence P availability in soils primarily by altering soil pH. Dual application

of APP+UAN resulted in higher total available and extractable P concentrations than APP alone because of changes in pH. In the acid soil, the dual treatment first increased, and later decreased, soil pH more than APP alone. Soil pH changes were not as pronounced in the alkaline soil as in the acid soil. However, in both soils, changes in pH likely allowed formation of more soluble P reaction products. Moreover, ammonium-N concentrations remained higher in the dual treatment than in the APP treatment, indicating a large portion of the applied N with P remained as  $\text{NH}_4^+$  in the fertilizer band for a long period of time after fertilization. Available P decreased with distance and approached levels similar to untreated soils in the last ring. Dual applications of APP and UAN did not show increased P availability in the outer rings as it did in rings 1, 2, and 3.

Extractable Zn, Fe, and Mn concentrations decreased with distance from the fertilizer bands. Treatment effects on extractable micronutrient concentrations generally corresponded to changes in soil pH for Fe and Mn. For Cu and Zn, however, extractable micronutrient concentrations often were lower for the treatment with the lowest soil pH. Although the reason for this could not be determined from the data collected, these results suggest that Zn and Cu availability would not increase as a result of additional nitrification and acidification when P is dual applied with ammoniacal N compared with P application alone.

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