

MAIZE YIELD RESPONSE AS AFFECTED BY PHOSPHORUS, SULFUR AND NITROGEN AS BANDED APPLICATIONS ON A VOLCANIC ASH DERIVED TROPICAL SOIL (1)

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ABSTRACT: Phosphorus and sulfur deficiencies have been observed on many of the volcanic ash derived soils in Central America. One exploratory experiment was initiated in 1987 to examine maize (*Zea mays L.*) grain yield response to phosphorus, sulfur and nitrogen applied together on a volcanic ash derived soil in the Pacific coastal plain of Guatemala. Four cycles of yield data were collected in 2 rainy and 2 dry seasons. Treatments consisted of rate combinations of N (0, 100 kg ha⁻¹ as urea), P (0, 22 kg ha⁻¹ as triple superphosphate) and S (0, 57 and 114 kg ha⁻¹ as CaSO₄·2H₂O) applied together in continuous bands in a randomized complete block design. Residual P and S response was measured during the last two cycles, whereby only urea was applied at a constant rate to all plots. The combined analysis of the first two cycles demonstrated a linear response of yield to applied S when no P was applied (4.95, 5.75 and 5.95 Mg ha⁻¹ at 0, 57 and 114 kg S ha⁻¹ respectively), while yield response was quadratic when S as CaSO₄·2H₂O and P as triple superphosphate were applied together in a continuous band at 100 kg N ha⁻¹ (5.38, 6.38 and 5.48 Mg ha⁻¹ at the same S rates respectively). Response of yield to S was linear without and with P for the combined residual analysis of the last two cycles at the same N rate (4.65, 4.94, 5.26 and 4.68, 5.53, 5.56 Mg ha⁻¹ respectively). Grain yields were maximized over

the four cycle period using a joint N, P, S band (100 kg. of N as urea, 22 kg P as triple superphosphate, and 57 kg S as $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ ha^{-1}). It is hypothesized that precipitation of dicalcium phosphate dihydrate (DCPD) and dicalcium phosphate (DCP) took place within the joint N-P-S band subsequently reducing the amount of P fixed as Fe or Al hydroxides and/or amounts of P complexed with amorphous allophane. The precipitation and subsequent dissolution of DCPD and DCP within the band could have increased P availability with time. Alternatively, SO_4^{2-} blocking of adsorption sites could have increased P availability by reducing the amount of P fixed by the soil. It is possible that both of the previously mentioned mechanisms played a role in first cycle yield responses since increases were noted at the low S rate (57 kg S ha^{-1}), while reductions were found when the S rate was doubled (114 kg S ha^{-1}). Significant residual response for the last two cycles was observed for the joint triple superphosphate, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, urea band, especially at the high S rate. This suggests that excess precipitation of DCP and DCPD could have occurred and that this provided delayed dissolution of the precipitated P reaction products. Chemical characterization of precipitated reaction products within the band is needed as well as further verification on similar soils in order to validate the observed response.

INTRODUCTION

Sulfur (S), phosphorus (P), and calcium (Ca) deficiencies are generally characteristic on volcanic ash derived soils. However, sulfur use efficiency is known to interact antagonistically with P and Ca applications (3,8,11,16). Elemental sulfur and ammonium sulfate have been used to correct S deficiencies, however, the use of this source can further accentuate soil acidity via oxidation processes. Although Pasricha and Aulakh (16) noted the importance of phosphorus and lime for groundnut production in India, both practices were found to decrease the sulfate retention capacity of the soil. There is also recent evidence to suggest similar S interactions with Zn, K, Mo,

and Se (21). Critical S levels in corn plant tissue have been determined but invariably showed poor correlation with yield (7,12).

Work by Blair and Lefroy (4), and the International Fertilizer Development Center (10), has indicated that S deficiencies can be found in soils derived from volcanic ash, due to the presence of allophane which can bind organic forms of S. The importance of allophane in volcanic ash derived soils relative to its fixation capacity for both P and S has been addressed by Okajima (15) and Tanaka (23). As stated by Okajima (15), "allophane has the marked tendency for aluminum to become active at low pH values." Furthermore, as weathering takes place, the leaching of bases and silica can leave the exchange complex dominated by aluminum and iron as well as reactive Al and Fe oxides (5). Due to the high P fixation capacities of volcanic ash soils, localized placement of P is necessary to reduce the surface area of the soil in contact with the fertilizer. Applications of superphosphate and potassium were found to induce magnesium deficiencies in volcanic soils in Japan (23). Blair and Lefroy (4) concluded that weathered tropical soils generally have a higher anion exchange capacity compared with temperate soils and a greater capacity to adsorb sulfate. Studies conducted by Chao et al. (6), dispute this point, suggesting that anion exchange was not involved in the retention of sulfate. Further work by Blair (5), noted the tendency for rapid removal of bases from the profile of soils formed in the humid tropics under high moisture percolation. Experiments reported by Pearson et al. (17), showed that 90% of all water soluble bases were leached as sulfate in acid Latosol and Red-Yellow Podzol profiles.

Annual burning of previous cycle residues prior to planting is common in most maize based production systems in Central America. This is done primarily to control *Phyllophaga* spp. and other soil born insects. This practice contributes to soil erosion and can volatilize up to 75% of the sulfur present in the organic residue (19).

Dicalcium phosphate dihydrate ($\text{CaHPO}_4 \cdot 2\text{H}_2\text{O}$) was found to form in

soils having a water-soluble calcium to magnesium ratio of approximately 1.5 or greater when orthophosphates were added to soils with varying Ca and Mg levels (18).

Methods of sulfur application in combination with other nutrients, particularly the use of consolidated band applications in minimum tillage systems have been given little attention in Central America. Therefore, the objective of this experiment was to determine the effectiveness of joint band applications of N, P, and S on maize grain yields in a minimum tillage system on a volcanic ash derived soil.

MATERIALS AND METHODS

In December, 1987 one maize (*Zea mays* L.) field trial was initiated near Cuyuta, Guatemala (100 m above sea level) to evaluate joint band applications of N, P, and S. Over a two year period, four cycles of yield data were collected (2 rainy seasons and 2 dry seasons) from this continuous experiment. The soils of this region have had the predominant influence of three nearby volcanoes, and receive 1400mm of precipitation/year. Generally, over 90% of the total rainfall is received during the months of May through October. Soils most commonly have a sandy loam texture. Composite soil samples at depths of 0-15 and 15-30cm were taken prior to treatment application and planting in December 1987 for site characterization and soil analysis (Table 1).

The experimental design was an incomplete factorial randomized complete block with three replications. No tillage operations were made in any cycle other than narrow furrows made in every other row parallel with replications to accommodate irrigation during the dry seasons (December 1987 and December 1988). Weeds were controlled by pre-plant applications of 'Atrazine' (2-chloro-4-ethylamino-6-isopropylamino-1,3,5-triazine) at 2 kg a.i. ha⁻¹, and 'Paraquat' (1,1'-dimethyl-4,4'-bipyridilium ion) at 2 l a.i. ha⁻¹. A Guatemala national program maize hybrid (ICTA HB-83) was hand

Table 1. Initial soil test characteristics, Cuyuta, Guatemala, 1987.

Depth cm	pH [†]	OM %	P [@] mg kg ⁻¹	K [#] ----- cmol(+) kg ⁻¹	Ca ^θ cmol(+) kg ⁻¹	Mg ^θ -----
0-15	5.9	4.1	6.0	0.57	6.23	2.87

† - 1:1, soil:water

@ - double acid extractable (0.05 N HCl + 0.025 N H₂SO₄)

- 1 M NH₄OAc extraction

θ - Thomas (24).

planted at a depth of 5 cm in December 1987, May, 1988, December 1988 and May 1989 respectively, at populations of 55,000 seed ha⁻¹. Plots consisted of six, 0.90m rows, 5.5 meters in length.

Urea (100 kg N ha⁻¹) was evaluated in combination with 0, 57 and 114 kg S ha⁻¹ as CaSO₄·2H₂O in a factorial arrangement, with (22 kg P ha⁻¹ as triple superphosphate) and without P. Other treatments were included as checks for N, P and S response outside of the factorial. Treatments 4 and 11 (100N 22P 0S) were identical and served to estimate treatment application accuracy (Table 2). Fertilizers were applied in the same continuous band prior to planting, 7 cm to the side and 7 cm below the seed on the West and East sides of the maize row in the December 1987 and May 1988 cycles respectively. Because residual P and S effects were of interest, the third and fourth cycles (December 1988, and May 1989, respectively) were treated as residual experiments whereby all plots received 100 kg N/ha as urea spot applied (5 cm below the surface of the soil, at 0.25 m intervals) in the center of the maize rows to avoid disturbance of bands made in the first two cycles.

Table 2. Treatment structure and maize grain yield means as affected by joint band applications of N, P, and S, 1987-89, Cuyuta, Guatemala.

Trt. #	N rate	P rate	S rate	--Treated Cycles--		Treated Mean	--Residual Cycles--		Residual Mean
				Dec. 87	May 88		Dec. 88	May 89	
----- kg ha ⁻¹ -----			----- grain yield Mg ha ⁻¹ -----						
1	100	0	0	5.51	4.39	4.95	3.89	5.40	4.65
2	100	0	57	6.58	4.91	5.75	4.56	5.32	4.94
3	100	0	114	7.34	4.56	5.95	4.62	5.90	5.26
4	100	22	0	6.09	4.67	5.38	4.13	5.24	4.68
5	100	22	57	7.45	5.31	6.38	5.17	5.90	5.53
6	100	22	114	6.41	4.54	5.48	5.48	5.64	5.56
7	0	0	0	5.36	1.28	3.32	3.33	4.57	3.95
8	0	22	0	6.77	2.25	4.51	4.97	5.76	5.36
9	0	0	114	6.13	1.05	3.59	4.47	5.76	5.11
10	0	22	114	4.55	1.12	2.84	3.64	4.38	4.01
11	100	22	0	6.53	4.34	5.43	4.39	4.93	4.66

N applied as urea, 46-0-0
 P applied as triple superphosphate, 0-46-0
 S applied as CaSO₄·2H₂O, 0-0-0-18.6

Table 3. Analysis of variance and associated contrasts for maize grain yield as affected by joint band applications of N, P, and S (Dec 87 & May 88), and residual (Dec 88 and May 89) cycles, Cuyuta, Guatemala, 1987-89.

Source of Variation	df	Dec 87 & May 88		Dec 88 & May 89	
		----- Mean Squares -----			
Replication(R)	2	4.26**		0.40	
Treatment(T)	10	8.09**		1.85**	
R x T (error a)	20	0.54		0.24	
Cycle	1	125.23**		13.94**	
Cycle x Treatment	10	2.68**		0.24	
Residual	22	0.21		0.17	
Coefficient of Variation, %		9.4		8.5	
CONTRAST					
(Treatment)					
P0, S rate linear	1	3.00*		1.14*	
P0, S rate quadratic	1	0.35		0.01	
P22, S rate linear	1	0.03		2.30**	
P22, S rate quadratic	1	3.61*		0.69	
0-0-0 vs. 0-22-0	1	4.26**		6.00**	
0-0-0 vs. 0-0-114	1	0.23		4.67**	
0-22-0 vs. 0-22-114	1	8.40**		5.49**	
100-0-57 vs. 100-22-57	1	1.20		1.05*	
100-0-114 vs. 100-22-114	1	0.67		0.27	
(Cycle x Treatment)					
Cycle x P0, S rate linear	1	2.08**			
Cycle x 0-22-0 vs 0-22-114	1	0.88*			

*, ** - significant at 0.05 and 0.01 probability levels respectively

Maize ears were hand harvested from 5 m of the center two rows, weighed and subsampled for moisture. A shelling percentage of 80 was used for final grain yield calculations. Initial soil test data for this site is listed in Table 1. Because the last two years were used to evaluate residual P and S effects, analysis of variance was conducted on the first two and last two cycles, respectively (Table 3). Linear, quadratic and various non-orthogonal contrasts were examined where appropriate.

RESULTS

December 87 and May 88 Cycles (Treated): Treatment means averaged for treated and residual cycles and by individual cycle are found in Table 2. A significant cycle by treatment interaction was found from the combined analysis performed on the first two cycles of yield data (Table 3). In general treatment response was similar for the first two cycles except for plots without N, and this accounted for much of the cycle by treatment interaction variance. Residual soil N levels were high in the first cycle, but were virtually depleted by the second cycle as can be observed in Table 2. A significant cycle by treatment interaction was also observed in the response to applied S when P was not applied (Table 3). The significant interaction contrast 'Cycle x P0, S rate linear' (Table 3) indicates that although a linear response of grain yield to applied S was present in the first cycle (5.55, 6.58 and 7.34 Mg ha⁻¹ at 0, 57 and 114 kg S ha⁻¹ respectively), no significant response to applied S was present in the second cycle (May 1988, 4.67, 4.91 and 4.56 Mg ha⁻¹ for the same S rates respectively). May and December cycles discussed differ in terms of both rainfall and soil temperature. As such, mineralization rates and the potential for increased leaching losses on these coarse textured soils are expected to be much higher for the wetter May cycle. Because this trial was initiated in the December cycle on land that had been continually tilled for the past twenty years, N immobilization during the dry December cycle was expected in these new minimum tillage plots. It is suggested that no

response to applied S was observed in the following May cycle because increased mineralization of organic S from the previous year's residue was expected during the rainy season.

The combined analysis of grain yield over the first two cycles indicated a linear response to S when no P was applied while S response was quadratic when P was applied at 22 kg P ha⁻¹ (Tables 2 and 3). Although the cycle by treatment interaction does not permit evaluation of the latter, main effects were of interest in light of data obtained from the two ensuing residual cycles. Where no N was applied a significant response to P was observed (0-0-0 versus 0-22-0). No response to S was observed when N was not applied (0-0-114 versus 0-0-0). When both P and S were applied without N, yields were reduced 1.67 Mg ha⁻¹ compared to P without N (0-22-0 versus 0-22-114). Response to applied P at the low S rate in the presence of N was not significant (100-0-57 versus 100-22-57).

December 88 and May 89 Cycles (Residual): The cycle by treatment interaction for the two residual cycles was not significant thus permitting independent treatment evaluation across the last two cycles. Yield response to previously applied S remained linear when no P was applied, while response to S when P was applied was linear, compared with the observed quadratic response in the first two cycles (Tables 2 and 3). A significant residual response to P applications made in the first two cycles was observed (+1.41 Mg ha⁻¹, 0-20-0 versus 0-0-0). Residual cycle yields were found to increase significantly when S was applied without N and P in contrast to the first two cycles (1.16 and 0.27 Mg ha⁻¹ for 0-0-114 and 0-0-0, respectively). Residual response to P and S applied together without N decreased yields compared to only P without N (-1.35 Mg ha⁻¹, 0-22-0 compared to 0-22-114).

Phosphorus applications at the 57 kg S ha⁻¹ rate with N increased yields 0.59 Mg ha⁻¹ in the two residual cycles (100-22-57 versus 100-0-57).

DISCUSSION

Yields of check plots without N in the December 1987 cycle indicated that residual N fertility levels were high at this site (Treatments 7-10, Table 2). In the ensuing May 1988 cycle, treatments receiving no N showed marked reductions in grain yield. A significant response to applied P was evident in the treated and residual cycles when comparing treatments 0-22-0 and 0-0-0 (1.19 and 1.41 Mg ha⁻¹, respectively). Alternatively, when N and P were not applied, S response was not evident in the first two cycles (0-0-114 versus 0-0-0). However, yield response to applied S was observed for the residual cycles when comparing these same two treatments. Because solubility of CaSO₄·2H₂O is known to be low and independent of soil pH, the slow dissociation of this S source could account for the different responses observed in the treated and residual cycles (0-0-114 compared to 0-0-0). Interestingly, when P and S were applied without N, yields were reduced compared to P and S alone in the first two cycles (0-22-114 versus 0-22-0 and 0-0-114, respectively).

The contrasting trends in S response observed in treated versus residual cycles when P, N, and S were applied together (quadratic and linear respectively for 100-22-0, 100-22-57 and 100-22-114) are difficult to explain (Tables 2 and 3). A yield depression was found when joint N-P-S bands were employed at the high S rate in the treated cycles (Tables 2 and 3), followed by a positive yield response in the residual cycles for 100-22-114. One possible explanation could be that almost complete inactivation of applied P (precipitation of P as dicalcium phosphate (DCP), dicalcium phosphate dihydrate (DCPD) and/or other forms including ammonium phosphate) took place at the high S rate, thus reducing yield to 0-P levels. If this were the case, then one would expect this treatment to yield equal to the 100-0-114 treatment which was not observed. Work by Lindsay (13) indicated that inclusion of cations such as NH₄⁺, K⁺, Ca⁺⁺, and Mg⁺⁺ in fertilizers enables

these cations to be included among the initial reaction products. Monocalcium phosphate (MCP, Ca(H₂PO₄)₂·2H₂O), which is the principal P source in ordinary superphosphate (OSP) and triple superphosphate (TSP), contains sufficient Ca⁺⁺ to precipitate half of the phosphorus as dicalcium phosphate or dicalcium phosphate dihydrate (13). In acid soils iron and aluminum generally precipitate the additional phosphorus which result in highly insoluble forms of P at low soil pH. Upon dissociation of the CaSO₄·2H₂O in the joint N, P, CaSO₄·2H₂O band, precipitation of DCP and DCPD may have taken place because of the presence of the added Ca⁺⁺. Given that these soils are known to have high P fixation capacities, DCP and DCPD could have been slowly available with time, thus reducing the amount of applied P fixed as unavailable Fe, and Al hydroxides and/or allophane P forms. Alternatively, SO₄⁼ blocking of anionic adsorption sites could help explain the apparent increased P availability when CaSO₄·2H₂O was applied. However, this does not account for the reduced yields observed at the high S rate in the first cycle.

In the treated cycle analysis, the 100-0-114 treatment had a non significant greater yield compared to 100-22-114 in the December 1987 cycle (Tables 2 and 3). It is hypothesized that in addition to having P precipitated in initially unavailable forms (DCP and DCPD) in the 100-22-114 treatment, ammonium phosphates may also have been precipitated reaction products. Work by Savant and Racz (20) has discussed the importance of P reaction products, particularly metastable intermediate products which are expected to dissolve with time. Decreased N availability as a result of having initial precipitation of ammonium phosphates from the joint 100-22-114 treatment compared to 100-0-114 appears to be a reasonable explanation for the observed tendency of increased yields in the two residual cycles for the 100-22-114 treatment. Work by Fenn and Taylor (9), indicated that the presence of additional Ca induced increased NH₄ absorption in *Raphanus sativus* L. as a result of having combined CaCl₂ and urea. In addition, Miller et al. (14),

demonstrated that decreased rhizosphere pH as a result of NH_4 uptake could increase $\text{H}_2\text{PO}_4^-/\text{HPO}_4^{2-}$ ratios thus increasing P availability. Characterization of the actual band in terms of pH changes with time and how this affects reaction products remains to be investigated.

Residual response for the check plot treatments receiving S, P or both (Treatments 8-10) was not consistent with observations made during the treated cycles, since the 0-22-114 treatment actually showed decreased yields in all cycles compared to 0-22-0 and 0-0-114. Apparently, N applied within the band is having an effect on availability of the precipitated products since no residual response was observed in the check treatment having both P and S. Whether this is due to an initially higher pH (urea hydrolysis) and a subsequently lower pH (nitrification) within the N-P-S band, or to the effect of NH_4^+ on precipitated reaction products is not known. Because previous research has demonstrated that the same P fertilizer can form many different P compounds of different solubilities in different soils (22), verifying these suggested reactions will require substantial laboratory analysis to identify actual precipitation reaction products.

CONCLUSIONS

Maize grain yield data was collected in 2 rainy and 2 dry seasons within a 2 year period on a volcanic ash derived soil in the Pacific coastal plain of Guatemala. Fertilizer treatments consisting of various combinations of N as urea, P as triple superphosphate and S as $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ were joint band applied in the treated cycles (December 1987 and May 1988). In the residual cycles (December 1988 and May 1989) all plots received only N to evaluate residual response to P and S applications. Grain yield response to applied P and S was evident in both the treated and residual cycles. Over the four cycle period, yields were maximized when N, P and S (100 kg N ha^{-1} as urea, 22 kg P ha^{-1} as triple superphosphate and 57 kg S ha^{-1} as $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) were applied together in a joint band 7cm to the side and 7cm below the seed. Although

yields decreased when S was applied with N and P at the high S rate (100-22-114) compared to 100-22-57 in the treated cycles, residual yields for 100-22-114 were at near maximum levels. By joint band applying triple superphosphate and $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, it is hypothesized excess Ca^{++} was available for formation of initial reaction products that included dicalcium phosphate (DCP) and/or dicalcium phosphate dihydrate (DCPD). Although DCP and DCPD would be very slowly available at low pH, this precipitation would reduce the amount of phosphorus complexed with amorphous allophane and/or precipitated as highly insoluble Fe and Al phosphates. By reducing the amount of P fixed in these highly unavailable forms as a result of precipitated DCP and/or DCPD, a slow release form of P may have been achieved. It is also possible that SO_4^{2-} blocking of positively charged adsorption sites may have decreased soil-P fixation when $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ was applied at the low S rate. Contrasting results from treatments receiving P and S with and without N in the residual cycle analysis, suggests that reaction products were altered when N was applied within the joint P-S band. However, it is apparent from the results obtained on this soil type that triple superphosphate and $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ should not be applied together (at the rates used in this experiment) without N. Future experiments will require substantial laboratory analysis to either validate or annul the hypothesis which have been proposed.

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