Agronomic Evaluation of Two Unacidulated and Partially Acidulated Phosphate Rocks Indigenous to Niger

A. Bationo, S. H. Chien,* J. Henao, C. B. Christianson, and A. U. Mokwunye

ABSTRACT

A field study was conducted on a sandy soil in Niger to evaluate the agronomic effectiveness of various P fertilizers for millet production during 1985 to 1987. The P fertilizers tested were two finely ground phosphate rocks (PR) indigenous to Niger (Tahoua and Parc W rocks), PR partially acidulated with H_2SO_4 at 50% acidulation level (PAPR), single superphosphate (SSP), and triple superphosphate (TSP). In 1985, application rates were 0, 6.5, 13.0, and 19.5 kg P ha^{-1} for each of the P fertilizers. In 1986, half of the plots received the same rates of P as in 1985 and half of the plots received no additional P. In 1987, P additions were repeated only in half of the plots that received P during 1986. A significant ($P = 0.05$) millet response to P was observed in all the trials. The major findings of this study were: (i) finely ground Tahoua PR was more effective than Parc W PR because of its higher reactivity and was 82 to 91% as effective as SSP for millet production in both the initial and two subsequent seasons; (ii) partial acidulation of Parc W PR can significantly increase its agronomic effectiveness in the first year, but not in terms of residual effect; (iii) partial acidulation was not a desirable technology for increasing the effectiveness of Tahoua PR, because its high Fe_2O_3 plus Al_2O_3 content resulted in a product containing relatively low amounts of water-soluble P; and (iv) over a period of 3 yr, one initial application of a large dose of P fertilizer was found to be more effective than three small annual applications in terms of total grain production.

PHOSPHORUS DEFICIENCY is a major constraint to crop production in West Africa (Bationo et al., 1986). In this region, use of P fertilizers is limited by the relatively high cost of imported fertilizers. However, direct application of PR indigenous to the region may be an economical alternative to the use of more expensive imported soluble P fertilizers for certain crops and soils. Some PR may not be suitable for direct application because of their low chemical reactivity (Hammond et al., 1986). Partial acidulation of PR represents a technology that may improve the agronomic value of an indigenous PR at a lower cost than would be required to manufacture the conventional, fully acidulated fertilizers from that same rock (Chien and Hammond, 1988; Hammond et al., 1986; Schultz, 1986).

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Recent laboratory and greenhouse studies by Hammond et al. (1989) showed that the $Fe_2O_3 + Al_2O_3$ content of PR can significantly influence the water solubility and agronomic effectiveness of PAPR. In their study, PAPR made from Kodjari PR in Burkina Faso (containing 7.1% $Fe_2O_3 + Al_2O_3$) at 50% acidulation with H_2SO_4 was found to be only 49% as effective as TSP in increasing dry-matter yield of maize (*Zea mays* L.). On the other hand, PAPR made from Hahotoe PR in Togo (containing 1.9% $Fe_2O_3 + Al_2O_3$) at 50% acidulation was 84% effective with respect to TSP.

Several PR deposits have been discovered in Niger. One of the two largest deposits, the Tahoua deposit, is near In Akker, approximately 63 km north-northwest of Tahoua, though the size of this deposit has not been quantified (McClellan and Notholt, 1986). In addition to this deposit, others have been discovered in the Parc W region south of Niamey in the Tapoa and Mekron Valleys near the Burkina Faso border. Resources in the Tapoa area along the Niger River are estimated at 1.25 billion Mg with 200 million Mg of reserve averaging 10% P (McClellan and Notholt, 1986). We present the results from a 3-yr study on the agronomic effectiveness of two indigenous PR (Tahoua and Parc W), with and without partial acidulation, for millet production in Niger under different application strategies.

MATERIALS AND METHODS

Fertilizer Materials

The finely ground rock samples were partially acidulated with H_2SO_4 by the single-step continuous process method, developed by the International Fertilizer Development Center (IFDC), in which acidulation and granulation take place simultaneously (Schultz, 1986). The quantities of acid used were 50% of the amounts of H_2SO_4 required for complete conversion of PR to SSP, calculated on the basis of the composition of the rock (Schultz, 1986). The PAPR products were in granular form, with sizes passing through a 3.35-mm screen but retained by a 1.18-mm screen.

Table 1 shows total, water-soluble, and citrate-soluble P contents in the original PR used and the PAPR produced. The table shows that the Fe_2O_3 plus Al_2O_3 content in Tahoua PR was higher than that in Parc W PR. The granular SSP and TSP used (Table 1) were obtained locally in Niger.

Field Evaluation

The soil at the study site, which was derived from eolian sand deposits, is representative of the soils presently being used for millet production in Niger. It is classified as a sandy, siliceous, isohyperthermic Psammentic Paleustalf. Some physical and chemical properties of the soil are: sand, 95%; silt, 3.5%; clay, 1.5%; pH (1 *M* KCl), 4.2; organic matter, 3 g kg^{-1}; effective cation-exchange capacity (1 *M* KCl), 0.64 $cmol_c\ kg^{-1}$; base saturation, 60%; total P, 73 mg kg^{-1}; and Bray 1 P, 2.0 mg kg^{-1}.

In 1985, each of four P fertilizers were broadcast before planting and incorporated at rates of 0, 6.5, 13.0, and 19.5 kg P ha^{-1}. Nitrogen was applied as urea in two equal splits at 2 and 6 wk after planting, for a total rate of 30 kg N ha^{-1}. Potassium was applied with the P fetilizer at planting at 20 kg K ha^{-1} as KCl. Millet was grown at a plant density of 30 000 plants ha^{-1} with three plants/pocket. The trial was planted using a factorial arrangement of three rates plus check and six sources with three frequencies of application. The experimental design was a split-plot design with five replications. The combination of P rates and sources plus two check plots without P were planted as main plots in 1985.

In 1986, each main plot (10 by 10 m) was divided into two subplots (5 by 10 m); one received additional P at the same rates as in 1985, and the other subplot was left as it was to allow the study of residual P effects. All of the treatments received N and K at the rates used in 1985.

In 1987, each subplot that had received P in 1986 was divided into two parts (2.5 by 10 m); one received additional P at the same rate as in 1986, and the other part received no P so that the residual effect could be studied. The rates of P applied during the 3-yr period are shown in Table 2.

The amounts of rainfall were recorded daily during 1985 to 1987 (Fig. 1). The total amounts of rainfall were 425 in 1985, 551 in 1986, and 508 mm in 1987. The rainy season in the region normally is from late May to October.

Table 1. Some chemical characteristics of phosphate rocks (PR) and partially acidulated phosphate rocks (PAPR) used in the study.

P source	Fe_2O_3 + Al_2O_3	Total P	Soluble P† Water	Soluble P† Citrate
	g kg^{-1}			
Parc W PR	29	124	0	90
Parc W PAPR	–	88	490	94
Tahoua PR	124	121	0	118
Tahoua PAPR	–	98	288	128
Single superphosphate	–	83	874	84
Triple superphosphate	–	211	798	187

† Grams of water- or citrate-soluble P per kilogram of total P.

Table 2. Rates of phosphate fertilizers applied to the test plots during 1985 to 1987.

Frequency	Initial and successive P applications 1985	1986	1987	Total
	kg/ha			
	0	0	0	0
(A)	6.5	0	0	6.5
(B)	6.5	6.5	0	13.0
(C)	6.5	6.5	6.5	19.5
(A)	13.0	0	0	13.0
(B)	13.0	13.0	0	26.0
(C)	13.0	13.0	13.0	39.0
(A)	19.5	0	0	19.5
(B)	19.5	19.5	0	39.0
(C)	19.5	19.5	19.5	58.5

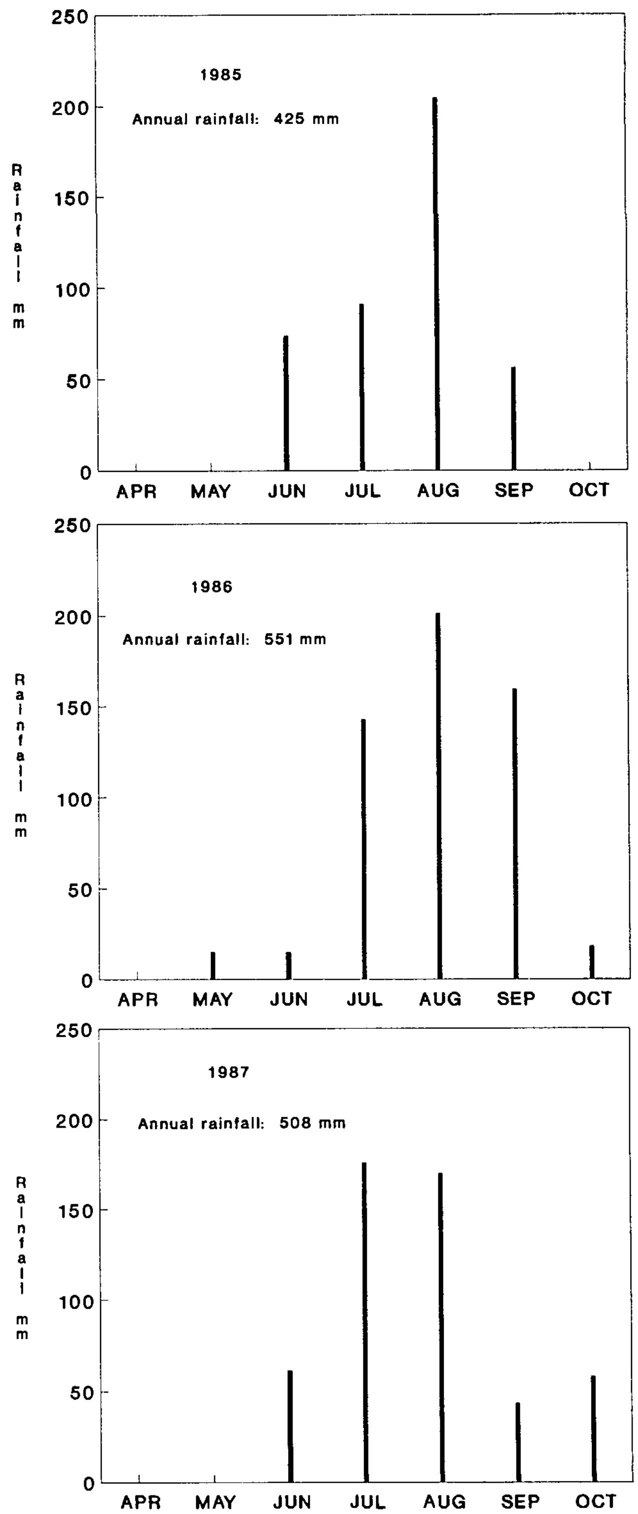

Fig. 1. Rainfall record at the study site in Gobery, Niger, during 1985 to 1987.

Statistical Evaluation

Agronomic evaluation of P sources was initially done by estimating the percent of variation in millet grain yield due to sources, P rates, and frequency of applications, according to the scheme of analysis of variance presented in Table 3.

Regression-analysis procedures (Draper and Smith, 1981, p. 200–295) were used to estimate response for P source and frequency of application as described in Table 2. Regression estimates for initial response and residual effects adjusted for rainfall variations were obtained according to the model

$$Y_i = \beta_0 + \alpha Z + \beta_i X^{0.5} + (\delta_{1i} + \delta_{2i})X^{0.5} + \varepsilon_i \quad [1]$$
$$i = 1,..,6 \text{ P sources}$$

where

Y_i = millet grain yield response in kg ha^{-1} for the ith source,
Z = total annual rainfall in mm during the cropping season for the years 1985 to 1987,
X = rate of P in kg ha^{-1} applied in 1985,
β_0 = average yield response of the plots without P application,
α = estimate of yield variations due to annual rainfall,
β_i = yield response per unit P to the ith source applied in 1985,
δ_{1i} = change in response in 1986 to the ith source applied in 1985,
δ_{2i} = change in response in 1987 to the ith source applied in 1985, and
ε_i = residual error.

Regression estimates for successive P applications during 1986 and 1987 (Table 2) were obtained according to the model

$$Y_i = \beta_o + \beta_i X^{0.5} + \varepsilon_i \quad [2]$$
$$i = 1,..,6 \text{ P sources}$$

where

Y_i = millet grain yield response in kg ha^{-1} and X = the rate of P applied in kg ha^{-1} during the current year,
β_0 = average yield for the current year of plots without P application, and
β_i = the response of the ith source applied during the current year.

The selection of Models [1] and [2] was made according to Tukey's method (Tukey, 1977), by plotting yield residuals against different X and Y transformations. Model estimates were obtained by ordinary least-squares method (SAS Institute, 1985). The Models [1] and [2] are consistent with adequate representation of functional relationships within the area and the data range of interest obtained in previous studies (Bationo et al., 1986).

Comparison of fertilizer sources for P efficiency of response was made by estimating an index using the β_i coefficients of Model [1] for initial and residual response and the β_i coefficients of Model [2] for successive applications. This index was called a relative agronomic efficiency (RAE) index:

$$\text{RAE}(\%) = \frac{\hat{\beta}_i}{\beta_{\text{SSP}}} 100 \quad [3]$$

It expresses the percent of change in yield obtained per unit of P applied with PR or PAPR sources, compared with a more soluble source like SSP (considered as standard and used in the area).

Agronomic evaluation of relatively long term (3-yr) strategies was made by estimating relative yield responses and cumulative yield increases for different P sources at the end of the experimental period in 1987. Millet yields were expressed as percent of maximum yield for this year. The following model was estimated:

$$Y_i^* = \gamma_{0i} - \gamma_{1i} \exp(-\alpha_i X) + \varepsilon_i \quad [4]$$

where

Y_i^* = millet grain yield for each source and frequency of application expressed as percent of the maximum yield in 1987, $\frac{Y_i}{Y_{(\max)}} 100$, [5]
γ_{0i} = the maximum yield obtainable or limiting yield to increasing rates of P for the ith source, expressed in percent,
γ_{1i} = the difference between the yields obtained with and without P, for the ith source, expressed in percent, and
α_i = the rate of change in percentage per unit of change in P to the remaining possible increase of the P response for the ith source.

The maximum millet yield, $Y_{(\max)}$ = 1289 kg ha^{-1}, was obtained in 1987 with three successive SSP applications of 19.5 kg P ha^{-1} each in 1985, 1986, and 1987. This value is within the range of those obtained in other trials for the same area (Bationo et al., 1986).

Model [4] represents a steady rise to a limiting value or yield. The estimates from the model are relative values for comparing frequency of application of fertilizer sources using PR or PAPR. Estimation of parameters of the model was made by using the Marquardt least-squares method for nonlinear-regression models (SAS Institute, 1985).

Table 3. Combined analysis of variance for millet grain yields as a function of frequency of application, P source, and application rates, during the 1985 to 1987 cropping period.

Source of variation	df	Sum of squares (SS)	Mean of squares
		% of total SS	
Blocks	4	1.3*	
Fertilizer sources (S)	5	20.6**	
P rates (R)	2	20.9**	
Sources × P rates (S × R)	10	3.6**	
(S × R) vs. check	1	9.0**	
Error(*a*)	72	16.8	60 340.1
Frequency of applications (F)‡	2		
A vs. (B + C)	1	7.0**	
B vs. C	1	3.1*	
Error(*b*)	8	1.1	35 625.6
F × S	10	1.4†	
F × (P rates + check)	6	1.7*	
F × S × (P rates + check)	20	2.6*	
Error(*c*)	144	10.9	19 592.6
Total corrected	284	100.0	
$S\bar{x}(c)$ = 140.0 kg ha^{-1}			
Mean = 815.8 kg ha^{-1}			
CV = 17.2%			
R^2 = 0.89			

†,*,** Significant at α = 0.10, 0.05, and 0.01 probability levels, respectively.
‡ Frequency A = one application in 1985, B = two successive applications in 1985 and 1986, and C = three successive applications in 1985, 1986, and 1987.

RESULTS AND DISCUSSION

Initial and Residual Effects from a One-Time Phosphorus Application

Significant millet grain yield variations due to combined effects of P rates, sources, and frequency of application were observed during the 3-yr trial. These variations, which accounted for about 70% of the total yield variation, are summarized in Table 3. Millet initial (1985) and residual (1986 and 1987) yields are

Table 4. Regression estimates and relative efficiency values for and residual effects of P sources and rates, following a one-time application in 1985, on millet grain yields during the 1985 to 1987 growing period.

P sources†	1985 Initial	1986 Residual	1987 Residual
Intercept: $\hat{\beta}_0$ = 680 kg			
Rainfall effect: $\hat{\lambda}$ = −0.76	$\hat{\beta}_i$	$\hat{\delta}_{1i}$	$\hat{\delta}_{2i}$
Tahoua PR	118.1**	6.9NS	12.3NS
Tahoua PAPR	66.7**	−12.8NS	−48.4*
Parc W PR	61.2**	25.5NS	9.2NS
Parc W PAPR	98.6**	−25.2NS	−15.8NS
SSP	143.9**	20.9NS	−1.3NS
TSP	124.7**	13.3NS	12.6NS
Mean yield (kg ha^{-1})	725.1	650.1	682.1
Syx = 99.2 kg ha^{-1}			
R^2 (adjusted) = 0.76			
n = 60			
	Relative agronomic efficiency index‡		
	%		
Tahoua PR	82.0b	75.8b	91.4a
Tahoua PAPR	46.3c	32.7c	12.8c
Parc W PR	42.5c	52.6c	49.3b
Parc W PAPR	68.5b	44.5c	58.0b
TSP	86.7ab	83.7ab	96.2a
SSP	100.0a	100.0a	100.0a

*,** Significant at α = 0.05 and 0.01 probability levels, respectively.
† PR = phosphate rock, PAPR = partially acidulated phosphate rock, SSP = single superphosphate, TSP = triple superphosphate.
‡ Values within a column with the same letter are not different at α = 0.01 probability level.

presented in Table 4. Significant responses (α = 0.01) to increasing rates of P were observed in those years. However, in 1986 and 1987, the changes in millet response to all the P sources that were applied in 1985 were statistically nonsignificant, except for Tahoua PAPR in 1987, where the decrease in response was very high and significant (α = 0.01). The response coefficients obtained with various P sources in 1985 ranged from 61.2 for Parc W PR to 143.9 for SSP, the least and most effective P sources for millet production in 1985, respectively.

The RAE values for the various P sources were calculated, considering SSP the 100% standard (Table 4). Direct application of finely ground Tahoua and Parc W PR were approximately 82 and 43% as effective as SSP in increasing millet grain yield initially (1985). Tahoua PR was more effective than Parc W PR because of its higher reactivity. The superiority of Tahoua PR over Parc W PR was also consistently shown in residual effects (1986 and 1987). Finely ground Tahoua PR was shown to be as effective as TSP in initial and residual effects; however, it was less effective than SSP in 1985 and 1986. No significant differences were observed between TSP and SSP either in the initial response (1985) or in the years that followed (1986 and 1987).

Partial acidulation of Parc W PR increased its RAE from approximately 43 to 69% in 1985 (Table 4). During the following 2 yr of cropping without additional P application, however, Parc W PR and Parc W PAPR were not significantly different, and both were significantly less effective than SSP in increasing millet grain yields. The results suggest that there is an initial benefit of increasing the water solubility of Parc W PR by partial acidulation; however, this effect tended to be reduced during the following years where no applications were made.

It was found that partial acidulation of Tahoua PR decreased the agronomic effectiveness with respect to the unacidulated PR during the 3-yr cropping period (Table 4). In 1985, Tahoua PR was 82% as effective as SSP, whereas Tahoua PAPR was only 46% as effective. In 1987, essentially no residual yield response was observed for the Tahoua PAPR applied in 1985, whereas finely ground Tahoua PR was as effective as SSP in terms of residual effects. The poor performance of Tahoua PAPR was due to the high Fe_2O_3 plus Al_2O_3 content in the rock, which caused the poor efficiency in producing water-soluble P during partial acidulation (Hammond et al., 1989). At 50% acidulation with H_2SO_4, Parc W PAPR had 49.0% of total P as water-soluble P, whereas Tahoua PAPR had only 28.8%. The sum of water-and citrate-soluble P of Tahoua PAPR (41.6%) was also less than that of Parc W PAPR (58.4%). This suggests that some of the water-soluble P in Tahoua PAPR was converted to citrate-insoluble P and thus became less available to the plant (Hammond et al., 1989). Furthermore, the agronomic effectiveness of the unacidulated PR component in the Tahoua PAPR granules was probably significantly reduced because of the large-granule-size effect (Chien and Hammond, 1978; Hammond et al., 1986).

Millet Response to Successive Phosphorus Applications

Significant interactions were observed among P sources, rates, and frequency of applications (Table 3). These results suggest that one source could respond differently in the soils of Niger depending on the P rate or the frequency of its application. The effects on millet grain yield of successive applications of P for each source are shown in Table 5. In general, the trends of crop response and relative agronomic efficiency of the sources in 1986 and 1987 were similar to those observed in 1985. Partial acidulation of Parc W PR increased its agronomic-response coefficient in 1987 from about 92 for Parc W PR to about 136 for Parc W PAPR, whereas the reverse was observed for Tahoua PR, which decreased its agronomic-response coefficient from 153 for Tahoua PR to about 92 with Tahoua PAPR after three successive applications.

Comparisons of the P sources in 1987, based on their RAE after three successive applications, showed that SSP, TSP, Tahoua PR, and Parc W PAPR were the most efficient sources of P, and that the less efficient sources were Parc W PR and Tahoua PAPR, which showed no significant differences (α = 0.01) between them. Similar results were observed in 1986 after two successive applications in 1985 and 1986 (Table 5).

Relative and Accumulated Millet Grain Yields under Frequency of Phosphorus Applications

Relative millet grain yields in 1987 are presented in Table 6 in terms of the yield obtained with three successive SSP applications (19.5 kg P ha^{-1} each in 1985,

Table 5. Regression estimates and relative efficiency values for successive applications of P sources and rates on millet grain yields, during 1985 to 1987 growing period.

P sources‡	Successive applications†		
	1986 (B)	1987 (B)	1987 (C)
Intercept $\hat{\beta}_0$	340.00**	410.0**	410.0**
Tahoua PR $\hat{\beta}_1$	147.0**	143.2**	152.8**
Tahoua PAPR $\hat{\beta}_2$	78.3**	59.8**	92.0**
Parc W PR $\hat{\beta}_3$	88.9**	78.1**	91.8**
Parc W PAPR $\hat{\beta}_4$	143.0**	90.4**	136.2**
SSP $\hat{\beta}_5$	219.5**	183.3**	200.8**
TSP $\hat{\beta}_6$	199.9**	152.4**	195.5**
Mean yield (kg ha^{-1})	844.8	846.9	979.6
Syx (kg ha^{-1})	115.2	149.6	94.1
R^2 (adjusted)	0.85	0.67	0.85
n	20	20	20
	Relative agronomic efficiency index§		
	%		
Tahoua PR	66.9b	78.1a	76.1b
Tahoua PAPR	35.7c	32.6c	45.8c
Parc W PR	40.5c	42.6c	45.7c
Parc W PAPR	65.1b	49.3bc	67.8b
TSP	91.1a	83.1a	97.3a
SSP	100.0a	100.0a	100.0a

*,** Significant at $\alpha = 0.05$ and 0.01 probability levels, respectively.
† Frequency B = two successive applications in 1985 and 1986, C = three successive applications in 1985, 1986, and 1987.
‡ PR = phosphate rock, PAPR = partially acidulated phosphate rock, SSP = single superphosphate, TSP = triple superphosphate.
§ Values within a column with the same letter are not different at $\alpha = 0.01$ probability level.

Table 6. Regression estimates relating percent of maximum millet grain yield in 1987 to P rates and sources for three frequencies of application. (Maximum millet grain yield in 1987 [19.5 kg P ha^{-1}] = 1289 kg ha^{-1}.)

P source‡	Frequency of application§	Phosphate source estimate†			
		γ_{0i}	γ_{1i}	α_i	$\hat{Y}_2$
		(%)			
Tahoua PAPR	A	37.5	3.4	.04	36
	B	50.2	13.3	.14	49
	C	64.0	30.5	.20	63
Parc W PR	A	45.2	12.4	.12	44
	B	52.5	18.1	.13	51
	C	61.4	23.4	.15	60
Parc W PAPR	A	70.3	37.4	.05	56
	B	72.9	39.4	.10	67
	C	74.6	40.4	.11	70
Tahoua PR	A	78.1	45.7	.07	66
	B	76.2	41.5	.10	70
	C	83.8	48.9	.11	78
TSP	A	85.5	50.6	.11	80
	B	94.7	58.3	.11	88
	C	96.0	59.5	.18	94
SSP	A	86.8	51.9	.12	82
	B	100.2	64.5	.11	93
	C	105.4	69.4	.13	100
Asymptotic standard error for SSP estimates		10.2	11.6	.10	

† γ_{0i} = the maximum yield obtainable or limiting yield to increasing rates of P for the ith source, expressed as percent; γ_{1i} = the difference between the yields obtained with and without P, for the ith source, expressed as percent; α_i = the rate of change in percentage per unit of change in P to the remaining possible increase of the P response for the ith source.
‡ PAPR = partially acidulated phosphate rock, PR = phosphate rock, TSP = triple superphosphate, SSP = single superphosphate.
§ Frequencies: A = one application in 1985; B = two applications in 1985 and 1986, and C = three applications in 1985, 1986, and 1987.

1986, and 1987). The sources are ordered according to the value of the estimate of the limiting response or maximum yield, γ_0, from Model [4]. The result shows that Tahoua PAPR was the least effective while TSP and SSP were the most effective for the different frequencies of application.

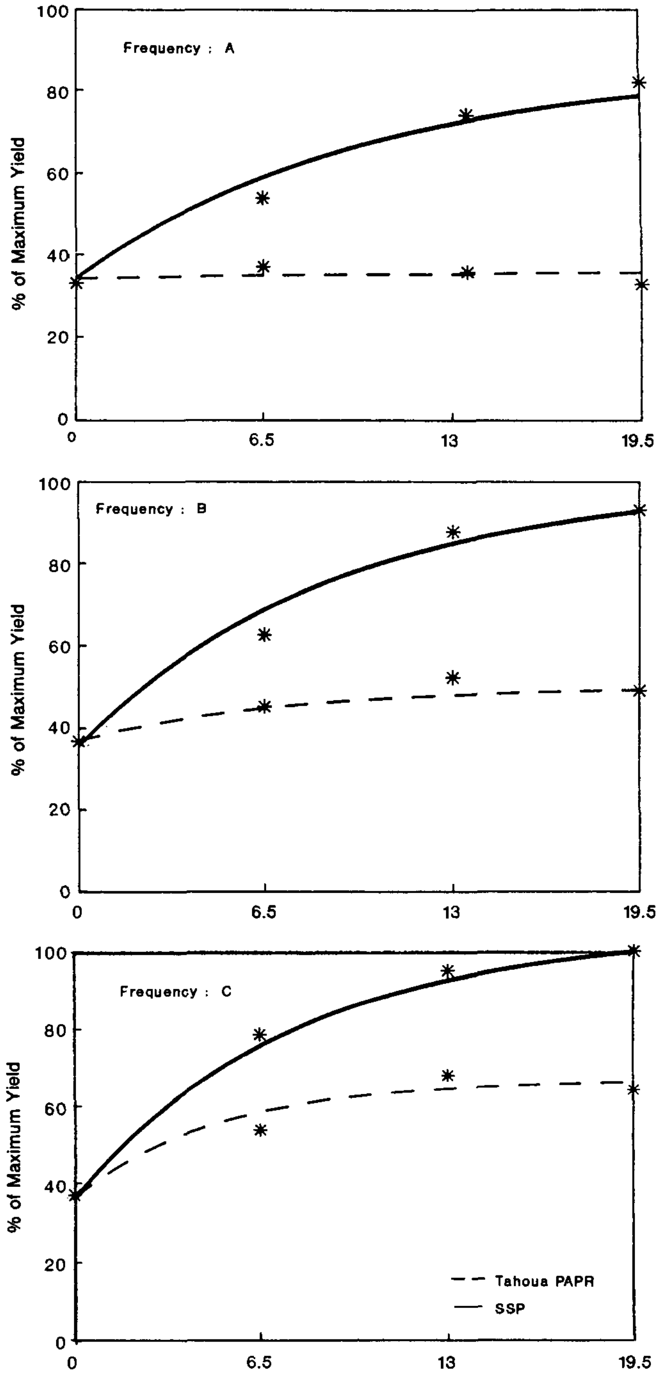

Fig. 2. Relative yield values in 1987 obtained at three frequencies of application of Tahoua partially acidulated phosphate rock (PAPR) and single superphosphate (SSP): (A) one application in 1985, (B) two applications in 1985 and 1986, and (C) three applications in 1985, 1986, and 1987. Maximum yield (1289 kg ha^{-1}) obtained with SSP using Frequency C.

Data in Table 6 show that the millet response to SSP in 1987 from a one-time application (19.5 kg ha^{-1}) in 1985 and from two successive applications in 1985 and 1986 (19.5 kg ha^{-1} each) were approximately 82% and 93%, respectively, with respect to three successive applications of SSP (19.5 kg ha^{-1} each). The corre-

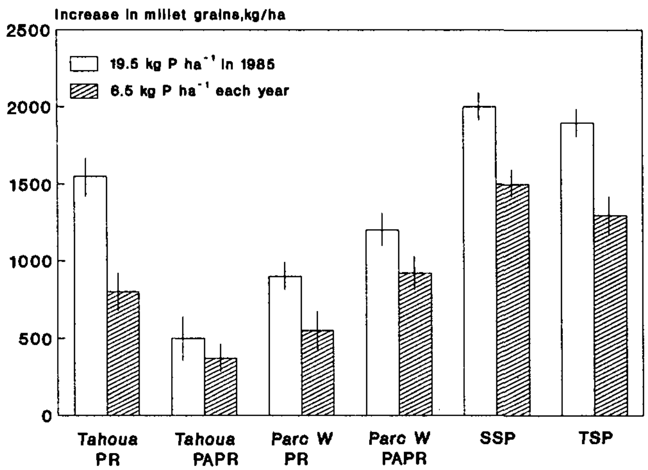

Fig. 3. Accumulated yield increase over the no-P control of millet grains (1985–1987) obtained with various P fertilizers at a total application rate of 19.5 kg P ha^{-1}. PR = phosphate rock, PAPR = partially acidulated phosphate rock, SSP = single superphosphate, and TSP = triple superphosphate.

sponding limiting yields were approximately 87%, 100%, and 105%, respectively, of the maximum yield in 1987 (1289 kg ha^{-1}) for the three frequencies of application. Conversely, millet yields for Tahoua PAPR were only 36% for a one-time application (19.5 kg ha^{-1}) in 1985 (Fig. 2A), 49% for two successive applications in 1985 and 1986 (19.5 kg ha^{-1} each) (Fig. 2B), and 63% for three successive applications in 1985, 1986, and 1987 (19.5 kg ha^{-1} each) (Fig. 2C). The corresponding limiting yields were 38%, 50%, and 64%, respectively (Table 6). These findings suggest that residual values of SSP are high in this soil, and frequent applications of SSP may not be needed. In contrast, successive applications of Tahoua PAPR would be needed because of its low residual effectiveness (Fig. 2).

It was found, at the end of the 3-yr trial, that the accumulated millet yield increase over the check obtained at a given rate of total P applied in 3 yr was higher for the P fertilizers applied only once in the 1st yr than for those applied in three equal splits in 3 yr. This is demonstrated in Fig. 3, which shows that the accumulated increases in grain yields over the check were higher for the P fertilizers (except Tahoua PAPR) applied only once in 1985 at a rate of 19.5 kg P ha^{-1}, than for those applied at 6.5 kg P ha^{-1} each in 1985, 1986, and 1987. This is due to the fact that the P-fixing capacity of this sandy soil is very low, so the initial and residual effects from a large dose of P applied only once was greater than from the same amount of P split-applied in small doses.

SUMMARY AND CONCLUSIONS

The agronomic results obtained in this study showed that, in terms of initial and residual effects, direct application of finely ground Tahoua PR can be almost as effective as SSP and TSP for millet production in Niger. The less reactive Parc W PR, however, was much less effective than SSP and TSP. Partial acidulation could increase its effectiveness, but continuous applications should be made. By contrast, partial acidulation of Tahoua PR decreased its effectiveness because the high Fe_2O_3 plus Al_2O_3 content of the rock caused the reversion of water-soluble P to citrate-soluble and citrate-insoluble P during acidulation.

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