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Use of rainfall indices to analyze the effects of phosphate rocks on millet in the Sahel

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Two critical factors that explain low crop productivity in the Sahelian agro-ecozone are inadequate moisture and poor soils, particularly phosphorus (P) deficiency. The purpose of this long-term study was to explore the use of both local phosphate rock (PR) and inorganic P on yields and risk of millet returns under the uncertain rainfall regimes in the Sahel. Using the Standardized Precipitation Index (SPI) and Percent Confidence Limits (PCL) of the mean rainfall, the 10-year experimental period was grouped into rainfall classes. Results showed that the inorganic P fertilizers, that is, single superphosphate and triple superphosphate (SSP+N and TSP) gave the highest average yields. Also, millet yield increased with increasing P rates. However, typical farmers in the Sahel barely use P rates above 20 kg ha^{-1} in view of the high cost of imported fertilizers. A low application rate of the local PR, 10 kg P ha^{-1}, increased millet yield between 44 and 67%. Stability analysis using yields from 15 farmers' fields indicated that the traditional method of growing millet was the least stable (s.e. = 225) and had the lowest yield (314 kg ha^{-1}). Generally, millet responded to P better when the preseason (May-June) were wet than dry, except where the non-acidulated PR (PRA) was applied every year (R^2=0.99, $P < 0.01$) for both dry and wet preseasons. Risk analysis showed that acidulated PR regardless of rates gave the highest millet returns over variable cost of P fertilizer. The study recommends the promotion PR in order to guarantee stable yields and income for small farmers in the Sahel.

Key words: Phosphate rock, Sahel, millet, variable rainfall.

INTRODUCTION

Two important factors that impede farming in the Sahelian environments are low soil fertility and low and irregular rainfall (Wallace et al., 1988; Sivakumar, 1990; Monteith, 1991; Pieri, 1992). In Niger, mean annual rainfall ranges between 300 and 700 with coefficient of variation of more than 60% (Sivakumar, 1990). Soils are sandy (98%) and generally low in organic matter and plant nutrients, especially phosphorus (Bationo et al., 1990). Deficiency of P in Sahelian soils often results in poor root development, poor growth and inefficient uptake of water and nutrients (Payne, 1990). Accordingly, yields of major crops such as millet, sorghum and cowpea are generally low and unstable (Bationo et al., 2007; Bationo et al., 1992).

Interventions that have been developed to reduce adverse effects of low and variable rainfall on crop yields and also to address the issue of poor soils are conservation tillage and crop residue mulch (Nicou and

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Table 1. Site characteristics at Sadore and description of phosphorus treatments.

Characteristics	**Mean values/description**
Rainfall (mm/year)	560
Temperature (°C)	29
Elevation (m)	240
Sand (%)	94
Organic matter (%)	0.22
Bray 1 phosphorus (mg/kg)	2.3
P sources	
PRA	Phosphate rock applied annually
PAPR25	25 % partially acidulated phosphate rock
PAPR50	50 % partially acidulated phosphate rock
TSP	Triple superphosphate
SSP+N	Single superphosphate + nitrogen fertilizer
SSP	Single superphosphate
PRB	Phosphate rock applied once every three years

Source: Bationo and Ntare (2000), Sivakumar (1990) and Manu et al. (1991).

Charreau, 1985), farm manure, green manure and agrofrestry (Kouame et al., 1994), mineral fertilizers including phosphate rocks (Bationo et al., 1992), integrated use of inorganic and mineral fertilizers, improved crop varieties and cultural practices, such as manipulation of planting dates, rotations and plant densities (Sivakumar and Salaam, 1999; Reddy et al., 1994).

As expected, impacts of these technologies on livelihood of farmers have been mixed and that can be explained by the fact that farmers' circumstances vary in terms of resource endowment, management styles and climate. Among climatic factors, rainfall is most crucial and difficult to forecast and control under peasant farming conditions where irrigation is rare. We hypothesize that some of the management interventions like fertilization and rotation lessen crop losses by damping the effects of bad climate. This hypothesis arises from an outcome of weather and management impact studies in Nebraska (Yamoah et al., 1998) where maize yields were higher and more stable in fertilized rotational systems than unfertilized monocultural systems.

The objective of this study is to explore the use of different phosphate rock sources on yields and stability of millet under the uncertain rainfall regimes in the Sahel. To be sustainable, P source must be locally available at affordable prices.

MATERIALS AND METHODS

The study was performed at Sadore (13° 15' N latitude, 2° 18' E longitude) of Niger. Weather and soil conditions of the site have been characterized and are reported in Bationo and Ntare (2000), Sivakumar (1990) and Manu et al. (1991). The study was conducted over a ten-year period from 1982 to 1993 with the exclusion of 1983 and 1991 when other crops were grown instead of millet. The experiment had three treatment factors, that is, P sources at seven levels, P fertilizer rates at five levels and two methods of application, either seasonally or a one-time application. The P sources described in Table 1 were: 1) PRA, 2) PAPR25, 3) PAPR50, 4) TSP, 5) SSP, 6) SSP-N and 7) PRB. All plots received nitrogen (N) at the rate of 30 kg ha^{-1}as urea except that of treatment six. The design was a randomized complete block with eight replications in order to minimize soil variability.

The on-station experiment was followed by reduced number of treatments on P management on 15 farm fields. The on-farm treatments were: 1) the traditional millet-based cropping systems; 2) improved, where millet is grown in association with cowpea; 3) placement of P with millet seed in the planting hole; and 4) SSP+N. The experimental design was the same as that of on-station and with four replications per farmer. The test crop was the pearl millet cultivars CIVT (110 days) recommended by the Ministry of Agriculture. Planting was done around June at planting density of 10,000 plants ha^{-1} and harvested in October. Plot size was 100 m^2 from 1982 to 1984, but was split into two thereafter, to examine the residual effects of the treatments.

Rainfall during 10 years of the experiment was classified according to two indices: The first index, the Standardized Precipitation Index, SPI (Guttman, 1999) and the second used percent confidence limits of the mean rainfall (Woodhead et al., 1970; Peterson et al., 1990). The SPI for a period is the difference between rainfall recorded and the long-term mean divided by the standard deviation. It is a moisture classification index and usually ranges from −3.0 to +3.0. A SPI value of zero means conditions are neither dry nor wet, that is, average. Values of SPI between −1.0 and zero are considered as mild stress zone and beyond the limits of −3.0 and +3.0 are viewed as extreme situations. This study uses long-term rainfall records (1921 to 1998) at Say, a nearby weather station to Sadore experimental site.

Regression equations were used to assess millet response to P in the dry and wet weather classes as determined by the SPI and PCL of the mean rainfall. Risk (R) is the downside of the confident limit around the millet returns over variable cost of fertilizer P and N (Y_r) and was calculated as: $R = Y_r-[(t_{n-1})\ (S_d)]/n^{1/2}$, where S_d is the standard deviation, n is the number of observations and t is the probability level of a one-tailed table (Hildebrand and Russell,

Table 2. Classification of May-June rainfall at the Sadore site based on the standardized precipitation index and percent confident limits (PCL) of mean.

Year	Total rainfall	PCL classification[1]	SPI value	Rainfall class[2]
1982	95.4	Average	-0.4	Mild stress
1983	201.1	Wet	1.3	Wet
1984	117	Average	0.0	Average
1985	52.1	Dry	-1.1	Stress
1986	86.3	Dry	-0.5	Mild stress
1987	61.4	Dry	-0.9	Mild stress-stress
1988	149.9	Wet	0.5	Moderately wet
1989	72.2	Dry	-0.8	Mild stress
1990	55.0	Dry	-1.0	Stress
1991	240.0	Wet	1.9	Wet
1992	113.1	Average	-0.1	Very mild stress
1993	91.2	Average	-0.5	Mild stress

[1]Rianfall classification based on Peterson et al. (1991); [2] the SPI classification based on McKee et al. (1993).

1996). The returns over variable cost was calculated as: $Y_r = (Y_m * P_m) - F_c$, where Y_m is the yield of millet, P_m is the average price of millet and F_c is the cost of fertilizer. The subsidized costs of fertilizer were: cfa 170 kg^{-1} of TSP, cfa 130 kg^{-1} of urea and cfa 50 kg^{-1} of local phosphate rock, according to the Central Store of the Ministry of Agriculture in Niamey, Niger. The government stopped the importation of SSP in 1988, therefore, we assumed the same price as TSP (cfa 170 kg^{-1}) for SSP in this long-term study, even though we are aware that TSP with a higher P concentration, usually cost a little more than SSP. Millet prices vary depending on the area and season. The average price of millet based on a survey of 84 markets was cfa 56 kg^{-1} with a range of cfa 30 kg^{-1} to cfa 105 kg^{-1}. Based on the aforementioned result, the method of risk assessment was compared with other simpler procedures, such as the number of years with yields falling below an arbitrary fixed target (Helmers et al., 1986). We used cfa 20,000 ha^{-1} as the threshold returns.

Stability analysis was originally proposed by Finlay and Wilkinson (1963) in order to evaluate crop varieties in diverse agroeclogical zones. The present study adopted a modified stability technique based on linear regression models of treatment yields with mean site yields, that is, environmental index, EI (Hildebrand and Russell, 1996). Stability analysis and risk probabilities served as indicators of robustness of the technologies under the real production settings. SAS was used for the analysis of variance, correlation and regressions.

RESULTS AND DISCUSSION

Information on the Sadore site and description of the phosphorus sources used for the study are presented in Table 1. The rainfall at Sadore (560 mm yr^{-1}) is low compared to other experimental sites, such as Bengou (850 mm yr^{-1}) and Tara (700 mm yr^{-1}) where similar studies were being run. Soils at Sadore are typical of soils in the Sahelian environment, in that, they are sandy and contain low organic matter content. Consequently, water and nutrient retention capacity of the soils were poor.

Planting of millet begins in June and therefore, preseason moisture content in May and June is crucial with respect to germination and crop establishment, which eventually determine yield. Agronomic and economic importance of preseason moisture has been noted by (Wilhite and Glantz, 1985) and the adverse effects of deficit preseason moisture on subsequent yield have been discussed by Yamoah et al. (1998) in rotational cropping systems in eastern Nebraska. Examination of preseason rainfall (May and June) over a 12-year period indicates tremendous variability. In general, rainfall deficit and elevated temperatures in August affect flowering and milk stages of millet production adversely (Bationo et al., 1990). However, this study indicated a weak ($P > 0.05$) correlation between yield and August rainfall. Our emphasis in the present study was to take advantage of the moisture conditions before planting in order to maximize fertilizer-use efficiency for increased yields. Planting of early maturing cultivars may be another way to avoid adverse effects of August weather stress on crops.

Rainfall classification and long-term yield

The 80% confidence limit (PCL) indicated that five out of the 12 years experimental period were dry, four were average and the rest wet. The rainfall grouping by the SPI appeared to correlate with classification of two years (1983 and 1991) as wet (SPI value >1.0), eight years as stressed (SPI between –2.0 and –1.0) or mild stressed (SPI values between –0.90 and zero), one year was moderately wet and one year was average (Table 2).

Effects of P sources, rates and application methods are shown in Table 3 for individual years. Phosphorus sources and rates were significant in all years regardless of rainfall conditions, but application method was significant in seven of the 10 years. Phosphorus source by rate interaction were also significant in most years.

Table 3. F values from the analysis of variance by year for long-term millet grain yield for applied phosphate rock from different sources, 1982-1993 Niger.

Source	Df	1982	1984	1985	1986	1987	1988	1989	1990	1992	1993
						F values					
P Sources	6	23.8***	4.2***	16.7***	8.2***	12.0***	42***	9.4***	7.5***	9.4***	28***
P Rates	4	188***	87***	111***	91.8***	99.3***	150***	30.6***	65.25***	69.3***	130.4***
Method M	1			11***	113***	19.3***	43***	43.9***	186.8***	25.7***	1.65
S x R	24	5.0***	2.1***	2.30***	1.15	1.56*	3.7***	1.24	0.95	1.5*	3.54***
S x M	6				1.25	1.6	1.9*	1.04	1.87*	0.51	0.74
R x M	4				8.15***	1.85	3.1*	3.7***	0.51	1.7	0.76
S x R x M	24										
Error	483										

This result underscores the importance of P fertilization for millet production all the time in the Sahel. Obviously, the magnitude of the responses (F-value) to overall yield varies from year to year depending on several factors including rainfall. The combined analysis of variance indicated that P rates are key determinant to millet yield (F-value=970) followed by P source (F-value=120) and year (F-value=60) (Table 4). Most of the two-way interactions were also significant. The seven-year data used for the dry matter analysis showed similar response to the main treatments and the two-way interactions.

Specific P sources and rates affected millet yields differently as demonstrated by significant F-values in both individual years and the combined analysis. According to Table 5, the imported fertilizers: SSP+N and TSP gave greater yields. Also, millet yield correlated with P rates; however, typical farmers in the Sahel seldom use P rates above 20 kg ha^{-1}. Even at the low rate of 10 kg P ha^{-1}, local P sources increased millet yield between 44 and 67%. In Niger, imported P fertilizes are more costly than local rock P fertilizers, therefore, for obvious reasons, it may be appropriate to promote the use of local phosphate rock as an amendment to increase yields. Millet response to small applications of P fertilizer may be due to the priming effects that solubilize the native soil P (Sivakumar and Salaam, 1999). Total native P in the soil has been estimated as 68 mg kg^{-1} (Bationo et al., 2000).

Stability analysis and millet response to P in different rainfall conditions

Studies on 15 farm fields revealed that millet yields on farms fertilized by hill placement of phosphate rock gave comparable yields with those fertilized with SSP+N and were more stable than the latter treatment (Figure 1). As well, slopes (*b*) of the regression lines of the phosphate rock (*b*= 1.26) and SSP+N (*b*= 1.18) were > 1.0 indicative of the potential to increase yields at favorable site conditions. The improved system of rotation millet and cowpea was more stable (b = 0.70) but yielded lower than the P fertilized plots. The traditional method of growing millet had the lowest yield (314 kg ha-1) and non-responsive to improving environment (b = 0.225). Millet responded significantly to P from the various sources in wet than dry preseason moisture. Under wet preseason, P was explained between 95 to 99% of variability in yield, whereas under dry conditions between 91 to 99%, was explained. Millet responded equally to P in both wet and dry preseason moisture when phosphate rock (PRA) is applied every year. The standard errors of estimate between the wet and dry moisture conditions were not significant. From management standpoint, it implies that it may be more advisable to fertilize with any of the P sources when May and June are wet than when dry. Millet response to P from either PAPR25 or PAPR50 source in dry weather was relatively weak and was only significant at the 9 and 10% level.

Averaged over P sources and methods of application, millet yield for the most recent five years were curvilinearly related to standardized May to June rainfall (Figure 2). The earlier varieties did not respond to standardized May to June rainfall. It could be that the newer cultivars are improved and are more responsive than the older cultivars to environmental resources and management, such as moisture and fertilizer application. Additionally, Figure 2 substantiates the influence of adequate preseason moisture in controlling yields based on the previous analysis on cereal production carried out by Thompson (1995), Teigen and Thomas (1995) and Yamoah.

Table 4. Combined ANOVA for grain and residue yields of millet as affected by years, phosphate rock from different sources and application methods.

Grain yields			Reside yields		
Source	**df**	**F value**	**Source**	**df**	**F value**
Year (Y)	9	60.34***	Years (Y)	6	279.06***
P source (S)	6	120.13***	P source (S)	6	58.77***
P rate (R)	4	970.24***	P rate (R)	4	364.91***
Method (M)	1	6.24***			
Y x S	54	5.09***	Y x S	36	2.02***
Y x R	36	11.27***	Y x R	24	6.34***
S x R	24	12.50***	S x R	24	5.31***
Y x S x R	216	1.10	Y x S x R	144	0.68
Y x M	9	35.22***			
S x M	6	1.14			
Y x S x M	54	0.97			
R x M	4	0.47			
Y x R x M	36	2.68			
S x R x M	24	1.09			
Y x S x R x M	216	0.5			
Error	4830		Error	1708	

Table 5. Effect of P sources and rates on millet yields (kg ha^{-1}), averaged over ten years and application methods.

P source	10	20	30	40
PRA	420	500	600	650
PAPR25	440	550	600	740
PAPR50	485	615	700	800
TSP	540	600	730	830
SSP+N	620	810	780	895
SSP	430	560	650	695
PRB	455	490	530	570

Control yield with no P = 290 kg ha^{-1}. Standard error of P sources x rates = 46.6.

et al. (2000). Furthermore, rapid early crop establishment and growth are advantageous because more leaves are produced to protect the soil from losing excess moisture, thereby increasing moisture-use efficiency of the system during the growing season (Sivakumar and Salaam, 1999)

Risk and economic considerations

Risk analysis of the long-term effects of P fertilizers on seasonal variability of millet yields are presented in Table 6. The high rate (40 kg ha^{-1}) of acidulated PR gave the highest returns over variable cost of fertilizer at the one percent probability level. This means that a farmer who applies 40 kg ha^{-1} of either 25 or 50% acidulated PR will earn an income larger than cfa 30,000 ha^{-1} in 99 out of a hundred years. Also, the use of the medium rate 20 kg ha^{-1} guarantees a minimum return of cfa 20,000 in 99 out of a hundred years (Table 6). Farmers who can afford to take on an additional risk at the five percent probability level could earn at least cfa 25,000 ha^{-1} when they apply 20 kg P ha^{-1} and up to cfa 38,000 ha^{-1} with high rate of 40 P kg ha^{-1}. However, with the application of 20 kg P ha^{-1} phosphate rock once in three years (PRB), farmers are assured of cfa 19,000 ha^{-1} 99 out of 100 years or cfa 21,000 ha^{-1} 95 out of 100 years. Thus, as low as 7 kg P ha^{-1} (that is, a third of 20 kg ha^{-1}) is required to alleviate poverty among millet growers in the sahelian region. Productivity will increase even further if farmers would combine the use of PR with animal manure or compost to improve aggregation of the predominantly structureless

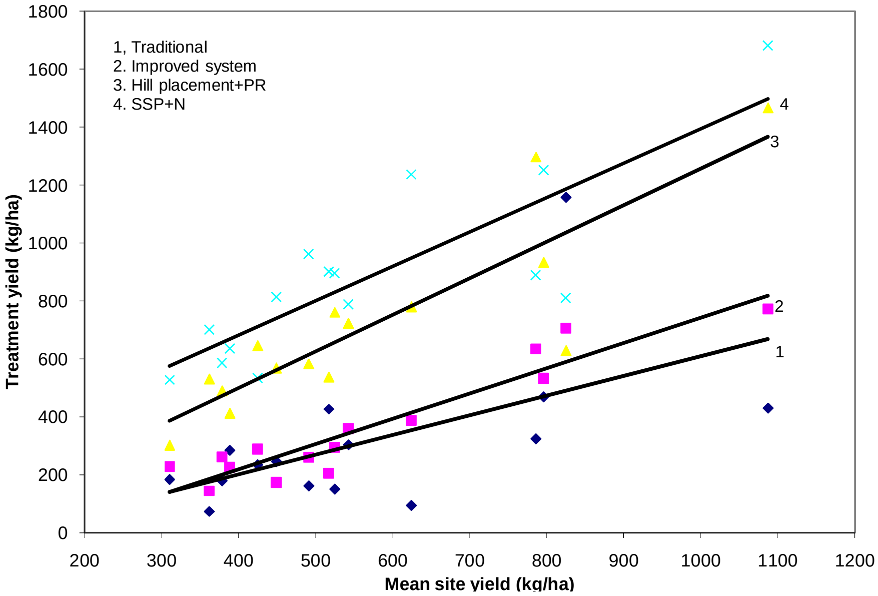

Figure 1. Stability analysis of millet yields as effected by P fertilization on farm fields.

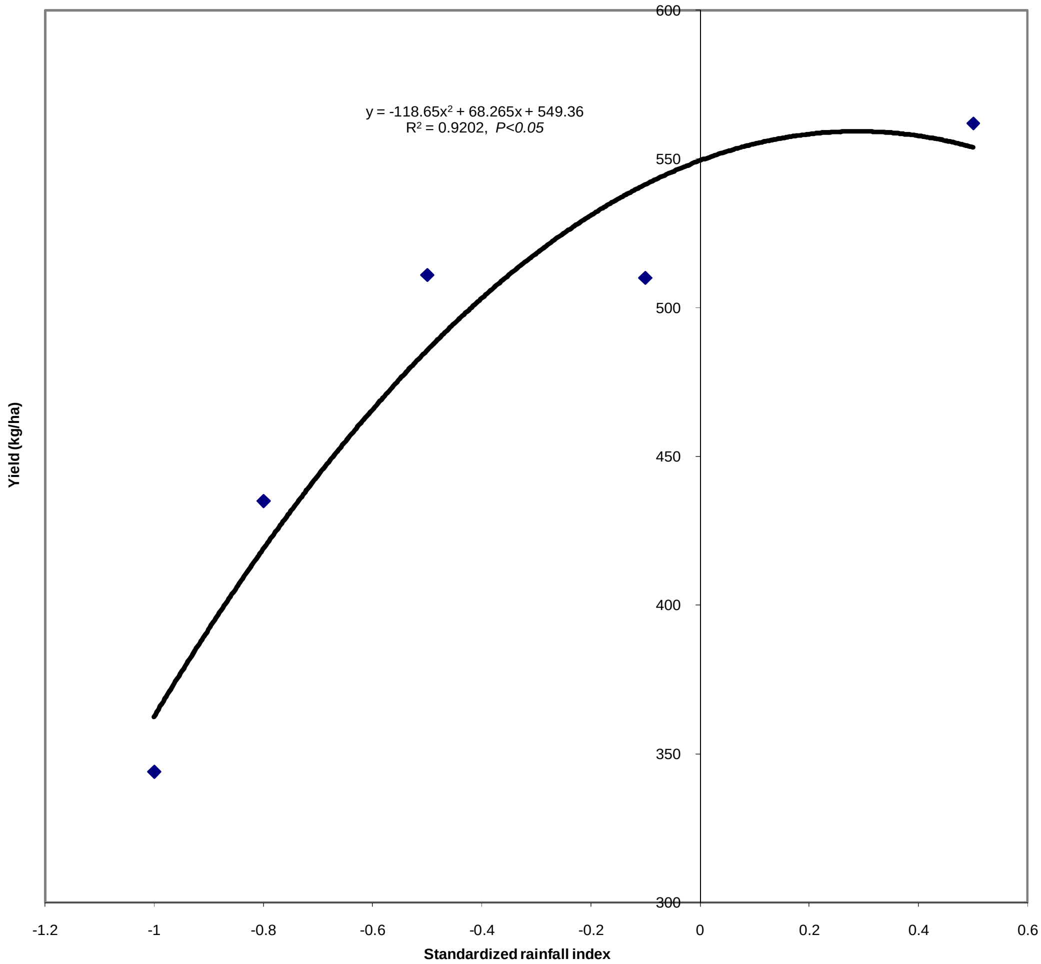

Figure 2. Millet response to standardized preseason rainfall in May and June.

Table 6. Risk analysis of millet returns from different phosphate rock sources over a 10-year period.

P source	Probability	Lower confidence limit of mean returns (cfa ha^{-1})		
	Level	Low P rates (0 kg P/ha)	Medium rate (20 kg P/ha)	High rate (40 kg P/ha)
PRA	0.01	10662	19713	26362
	0.05	12578	22194	29202
	0.10	13466	23344	30520
	0.20	14489	14629	31993
PAPR25	0.01	10622	23500	31723
	0.05	12542	25624	34338
	0.10	13432	22608	35550
	0.20	14427	27709	36909
PAPR50	0.01	10662	26420	35678
	0.05	12578	28833	38188
	0.10	13466	29952	39352
	0.20	14458	31204	40654
TSP	0.01	10659	22949	30619
	0.05	12574	25509	33685
	0.10	13461	26697	35106
	0.20	14454	28024	36695
SSP+N	0.01	10662	30340	30110
	0.05	15778	33008	33323
	0.10	13466	34244	34813
	0.20	14458	35628	36478
SSP	0.01	10659	20509	23691
	0.05	12574	23113	26591
	0.10	13461	24320	27936
	0.20	14453	25671	29439
PRB	0.01	10662	19347	20897
	0.05	12578	21745	23697
	0.10	13466	22856	24995
	0.20	14458	24099	26446

partly satisfy the N needs of the cereal crops and also to soils of the Sahel (Zingore et al., 2007; Batjes, 2001).

One simple measure of risk is the number of years in which returns fall below an arbitrary threshold value, say cfa 20,000. The results show that the acidulated PR fertilizers are comparable to or better than the TSP and the SSP+N fertilizers.

This study concludes that although the inorganic fertilizers gave high yields of millet, farmers are better off using local PR, so as to ensure high and stable income. Producers may also take advantage of wet preseasons P and N fertilization to maximize their yields and returns.

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