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A farm-level evaluation of nitrogen and phosphorus fertilizer use and planting density for pearl millet production in Niger

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Abstract

Mineral fertilizer use is increasing in West Africa though little information is available on yield response in farmers' fields. Farmers in this region plant at low density (average 5,000 pockets ha^{-1}, 3 plants $pocket^{-1}$), which can affect fertilizer use efficiency. A study was conducted with 20 farmers in Niger to assess the response of pearl millet [*Pennisetum glaucum* (L.) R. Br.] to phosphorus and nitrogen fertilizers under farm conditions. In each field, treatments included control, single superphosphate (SSP) only, SSP plus N (point placed near plant), and either SSP or partially acidulated phosphate rock (PAPR) plus N broadcast. N and P were applied at 30 kg N ha^{-1} and 30 kg P_2O_5 ha^{-1}. Farmers were allowed to plant, weed, etc., as they wished and they planted at densities ranging from 2,000 to 12,000 pockets ha^{-1}. In the absence of fertilizer, increasing density from 2,000 to 7,000 pockets ha^{-1} increased yield by 400%. A strong interaction was found between fertilizer use and density. Farmers planting at densities less than 3,500 pockets ha^{-1} had average yields of 317 kg grain ha^{-1} while those planting at densities higher than 6,500 pockets ha^{-1} showed average yields of 977 grain ha^{-1}. Though phosphate alone increased yields significantly at all densities, little response to fertilizer N was found at densities below 6,000 pockets ha^{-1}. Significant residual responses in 1987 and 1988 were found to P applied in high-density plots in 1986. Depending on fertilizer and grain prices, analysis showed that fertilizer use must be be combined with high plant density (10,000 pockets ha^{-1}) or no economic benefit from fertilizer use will be realized.

Introduction

A particular farm management practice is often less effective in the hands of the farmer than it is in a researcher-managed plot. Experimental farm input packages in development agriculture should therefore be tested under farmers' conditions before their release to extension services. This would allow the scientist to observe transfer of techniques to the farmers' fields and to determine associated management practices (herbicides, plowing, etc.) to be adopted in order to ensure good economic returns. In the absence of these associated inputs, the efficacy of a management practice in the farmers' hands may be reduced significantly.

Numerous studies in the Sahel have shown that only in the presence of adequate P will a yield response to other nutrients be found for pearl millet (*Pennisetum glaucum* [L.] R. Br.) [Traoré, 1974]. Use of phosphate promotes rapid growth of the plant, allowing it to better withstand adverse weather conditions early in the season. However, even in the presence of adequate N and P, the response of millet to fertilizer is highly dependent on midseason rainfall and planting density [Christianson et al., 1990; Bationo et al., 1990b].

The efficiency of fertilizer use is also often related to placement. Phosphate is generally not very mobile in the soil and it must be placed in a moist zone of the soil in order for the plant to derive maximum benefit. Similarly, the efficiency of nitrogen is often improved by incorporation as losses due to ammonia volatilization are reduced [Hauck, 1984] and the presence of subsoil moisture permits root proliferation and enhanced fertilizer uptake. However, millet farmers in Niger do not normally plow their fields and therefore cannot easily incorporate their fertilizers. Because the climate is dry, farmers use very low planting densities averaging 5,000 pockets ha^{-1}, 3 plants/pocket – about 1.4 m between pockets [McIntire, 1986]. Thus, the practice of banding or broadcasting fertilizer places a large fraction of the nutrients away from the plant. Even when the nationally recommended planting density (10,000 pockets ha^{-1}) is used, more than 50% of the fertilizer that is applied as a band or broadcast treatment is farther than 25 cm from the plants. In order to have the fertilizer near the plant and achieve placement below the soil surface, point placement in a small hole near the plant has been recommended in other African environments [Brown, 1966].

Zero-till studies in some developed countries have shown that the efficiency of surface-applied P is often equivalent to that of incorporated P [Singh et al., 1966]. This effect is largely due to the higher moisture levels in the surface soil layers caused by the maintenance of a trash layer [Engelsted and Terman, 1980]. In Niger, however, stover is normally used as a building material, animal feed, or source of fuel, and therefore little surface cover remains at planting. Under such conditions, the sandy soil texture (>90% sand) allows rapid surface drying, which would limit the efficiency of surface-applied nutrients. However, due to the very low P fixation capacity of the soils of this region, some P can move with infiltrating rainfall to lower depths [Mokwunye et al., 1986].

Although the soils of Niger are generally deficient in P, a large phosphate rock deposit is located in the Parc W region of the country. This phosphate rock (PR) is not very effective if applied directly as a ground material, but its reactivity may be improved by partial acidulation [Bationo et al., 1986]. Using this process, in which only a portion of the H_2SO_4 required to make single superphosphate (SSP) is added to the phosphate ore, increases the plant-available P content of the rock and thus increases its effectiveness as a P fertilizer. Field trials with Parc W partially acidulated phosphate rock (PAPR) have proven it to be 80%–90% as effective as SSP [IFDC, 1988]. Most P fertilizer sources tested in Niger have been shown to have a strong residual effect and have therefore benefited crops several years after initial application [Bationo et al., 1990a].

On the basis of previous research programs, scientists at the International Fertilizer Development Center (IFDC) and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) have developed several recommendations of fertilizer management practices for the small farmer in Niger. The trials discussed in this paper were established to test the farmer's use of several of these recommended practices for millet production in Niger.

Materials and methods

Experiments were initiated in 1986 at Gobery, a village 120 km southeast of the capital, Niamey, Niger. The soils in the study area are sandy psammentic Paleustalfs (sandy, siliceous, isohyperthermic). In a previous survey of 30 farms of this village (unpublished data, B. Christianson), soils were found to be very sandy (average 95.1% sand, range from 92.8% to 96.8%) and acidic (average pH [KCl] 4.9, range from 4.0 to 5.7) with low organic matter content (average 0.35%, range from 0.2% to 0.5%). The climate in this region is hot and the annual mean maximum air temperature is 36°C [Sivakumar, 1986]. Rainfall is generally received during the period from late May until early October with very little precipitation in the winter months (Table 1).

Four 25-m × 25-m plots were laid out in fields of 19 participating farmers; each farmer used four of five possible treatments (Table 2). The

Table 1. Total monthly rainfall at experimental site as compared to long-term averages at Niamey

	Normal[a]			Monthly rainfall at Gobery		
	Rain	T_{max}	T_{min}	1986	1987	1988
	(mm)	(°C)	(°C)	(mm)		
March	3	39.0	22.8	0	0	0
April	7	40.9	26.3	0	0	0
May	35	39.9	27.4	15	0	0
June	75	36.9	25.4	15.2	61.2	13.7
July	141	33.7	23.6	142.8	176.0	162.4
August	191	32.1	22.9	201.0	170.1	297.7
September	89	33.9	23.3	159.3	43.4	155.9
October	16	37.4	23.6	18.1	57.9	0
Total	557			51.4	508.5	729.7

[a] Based on 74 years of data from Niamey, 90 km northwest of Gobery [Sivakumar, 1986].

Table 2. Fertilizer treatments used by farmers in trials

Treatment	Fertilizer placement	N rate	P rate	Number of participating farmers		
				1986	1987	1988
		(kg N ha^{-1})	(kg P_2O_5 ha^{-1})			
1. Check	–	–	–	19	16	16
2. SSP[a]	Broadcast	0	30	19	16	16
3. SSP + N	Hill Placed	30	30	19	16	16
4. SSP + N	Broadcast	30	30	10	8	8
5. PAPR[b] + N	Broadcast	30	30	9	8	8

[a] SSP – Single superphosphate.

[b] PAPR – Partially acidulated phosphate rock – (50%) prepared using Parc W rock (Niger) and sulfuric acid.

fertilizer rates (30 kg P_2O_5 ha^{-1}, 30 kg N ha^{-1}) were chosen on the basis of researcher-managed trials previously conducted in the region. The trials were established with no replications, and each farmer (site) served as a single replicate. Farmers were given the fertilizers before planting and were allowed to choose when to conduct all operations including date (as well as method) of planting, date of fertilizer application, and harvesting. The only restriction was that N be applied in two splits – one-half 2–3 weeks after planting and the rest 3 weeks later. Observers living in the village recorded the time that each operation was performed and measured plant density and crop yield parameters at harvest. In the broadcast fertilizer treatments, P was applied before planting, and for hill placement, P was applied with the first N split at 2–3 weeks after planting.

In 1987, the experiments were continued with 16 participant farmers and the plots were split into two equal parts. In one subplot, the trial was repeated as in the previous year. In the other subplot, no additional fertilizer was applied so that the residual effects of the fertilizer applied in 1986 could be studied. The N sources used in the experiments were urea (1986) and calcium ammonium nitrate (1987 and 1988). In 1988, 16 farmers remained in the study and the subplots that had received fertilizer in 1987 received it again, while the subplots used for the residual study in the previous year did not receive any fertilizer.

Statistical analysis

Exploratory analyses were performed to characterize the sample with respect to density. The data from all farmers for the 3 years, excluding the unfertilized treatment, were used with the

UNIVARIATE procedure of SAS [1985] to calculate the mean, standard deviation, and quartiles and to test normality. Analysis of variance was then performed for grain yield using the quartiles as density levels.

$$y_{ijk} = \mu + A_i + T_j + D_k + (AT)_{ij} + (AD)_{ik} + (TD)_{jk} + (ATD)_{ijk} + \epsilon_{ijk} \qquad (1)$$

where

μ = overall mean
A_i = i^{th} year effect ($i = 1, 2, 3$)
T_j = j^{th} treatment effect ($j = 1, 2, 3, 4, 5$)
D_k = k^{th} density quartile effect ($k = 1, 2, 3, 4$)

$(AT)_{ij}$, $(AD)_{ik}$, $(TD)_{jk}$, = interactions and $(ATD)_{ijk}$

ϵ_{ijk} = residual component

Regression analysis was used to study the effect on grain yields of the different variables measured in this research (P fertilizer, P plus N fertilizer, density, and their interactions). Variable selection procedures based on the results of the three experiments were used to develop a regression model that would maximize fit and minimize the standard error of the mean. The selected regression model was then used to estimate total cost and profit for different planting densities with varying fertilizer:millet price ratios. The different price ratios were obtained by leaving the millet price constant and varying the price of N and P fertilizer. The data obtained were used to determine the ratio of the value of the increased grain production above that of the unfertilized treatment to the cost of the fertilizer required to obtain such production (value:cost analysis) for different fertilizer:millet price ratios.

Results and discussion

The long-term average rainfall for the region is 557 mm; rainfall approached this average in 1986 (551 mm) and was slightly lower than normal in 1987 (509 mm) (Table 1) resulting in average yields of 690 kg grain ha^{-1}. In both seasons, early rainfall distribution was good though a drought period late in the 1987 growing season prevented the crop from reaching its yield potential. In 1988, abnormally heavy rainfall in August and September (453.6 mm; year total 732 mm) promoted disease and insect problems (*Raghuva albipunctella*, Joannis), which resulted in diminished yields.

The farmers were permitted to follow traditional planting practices, and the planting densities chosen were widely diverse. Densities used were generally low, averaging 5,300 pockets ha^{-1} in 1986; only two farmers approached or exceeded the nationally recommended density of 10,000 pockets ha^{-1}. The results of the characterization of the sample density are shown in Table 3. The Kolomogorov test used in the UNIVARIATE procedure of SAS (1985) indicated that the data were normally distributed. The general ANOVA indicated that yield was significantly affected by the density, the treatment, and the year (Table 4). Interactions between year by treatment and density by treatment were also found.

In a comparison of the five treatments over 3 years, millet showed a significant response to fertilizer, and annual application of 30 kg P_2O_5 ha^{-1} without supplemental nitrogen resulted in yield increases of 125% (Table 5). Treatments that received nitrogen in addition to phosphate showed a 181% increase over controls. No significant difference was found between PAPR and SSP, nor was a difference found between SSP plus N broadcast and SSP plus N hill placed. However, crop response to fertilizer use was strongly affected by the cropping density chosen by the individual farmers.

Table 3. Characterization of the sample density (3 years, treatment without fertilizer not included)
N = 136
Mean = 5,299 pockets ha^{-1}
SD = 2,300 pockets ha^{-1}
Test of normality: $P < 0.05$

Quartile	Density
Max	12,550
Q3	6,450
Median	5,030
Q1	3,500
Min	1,340

Table 4. ANOVA for 3 years (annual fertilizer application), dividing the density values by quartiles

Source	df	Mean square	F value
Density (D)	3	1,166,484	**
Year (Y)	2	1,014,364	**
Treatment (T)	4	626,329	**
D*T	12	57,744	*
Y*T	8	93,502	**
D*Y	6	30,378	NS
D*T*Y	17	31,455	NS
Error	145	32,133	–
Selected contrasts:			
PAPR + N vs. SSP + N			NS
Hill placed vs. broadcast			NS

Table 5. Millet grain yields by treatment (mean of 3 years)

Treatment	Yield
	(kg ha^{-1})
Control	261
SSP only	586
SSP + N hill placed	700
SSP + N broadcast	751
PAPR + N broadcast	752
$LSD_{0.05}$	84

Averaged over all fertilized treatments and all years, crop density was shown to have a very significant effect on millet yield. When farmers in the lower density quartile planted at less than 3,500 pockets ha^{-1}, yields were very low (317 kg ha^{-1}) and no response was found to fertilizer use (Table 6). However, each 1,500 pocket ha^{-1} increase in crop density resulted in a significant yield increase of approximately 200 kg grain ha^{-1}.

Several regression models were developed and tested to describe the effect of annual applications of P fertilizer and N fertilizer, plant density, and their interactions on the grain yield for both years of research. The strong effect of density on yield was evident in all treatments (Fig. 1). In the absence of fertilizer inputs, increasing density from 2,000 to 7,000 pockets ha^{-1} (the highest density achieved without fertilizer) increased yield by approximately 450 kg. Over the density range of 2,000 to 12,000 pockets ha^{-1} that was found in the fertilized plots, addition of P alone increased yield 490 kg above that of the control to give a yield benefit of 16.3 kg grain/kg P_2O_5. However, increasing density did not greatly enhance the yield response to phosphorus. Since the P + N response was not statistically different if the fertilizers were hill placed or broadcast, or if PAPR was substituted for SSP (Table 4), all three P + N treatments were combined to yield a single P plus N regression variable. The similarity in response of millet to either broadcast SSP + N or PAPR + N indicates that both sources were equally effective P sources over the densities tested during the 3-year period of the study.

Table 6. Millet grain yields by density group (quartile)

Density	Yield
(1,000 pockets ha^{-1})	(kg ha^{-1})
<3.50	317
3.51 – 5.00	506
5.01 – 6.45	733
>6.45	977
$LSD_{0.05}$	73

The response to N + P relative to P only or control treatments was highly dependent on crop density. At densities below 3,000 pockets ha^{-1}, no response to P + N was found. However, as density was increased to 10,000 pockets ha^{-1} and N demand rose, a millet response of an additional 333 kg grain over the P only treatment was predicted.

Since crop density in this study was so low (average 5,300 pockets/ha^{-1}), it was expected that placement of fertilizer near the plant would improve yield response. However, although hill-placed (HP) fertilizers tended to result in lower yields compared with fertilizers that had been broadcast, the difference was not significant (Table 5). This lack of enhanced yield response was probably due to the different timing of P application; point-placed P was applied 3 weeks after planting, whereas broadcast P was applied before seeding. Thus, for a period of 3 weeks, the HP plants were growing without benefit of P fertilizer. However, placement of N and P below the surface and near the plant roots may have partially compensated for the late fertilizer application. This practice would be expected to improve fertilizer uptake efficiency and increase P response. Because the average densities were only 5,000 pockets ha^{-1} (1 pocket/2 m^2), most of the broadcast fertilizer would not have been

Table 7. Residual effects in 1987 and 1988 of fertilizer applied in 1986 as affected by crop density

Treatment	Grain yield			
	1987		1988	
	Low density[a]	High density[b]	Low density	High density
	(kg ha^{-1})			
Control	250	410	102	275
SSP broadcast	405	640	146	320
SSP + N broadcast	440	545	170	–[c]
SSP + N hill placed	440	665	163	404
PAPR + N broadcast	480	585	175	409
LSD$_{0.05}$	135	135	88	88

[a] Density of fertilized plots <5,000 pockets ha^{-1}.
[b] Density of fertilized plots >5,000 pockets ha^{-1}.
[c] No high density plot for this treatment in 1988.

close to the plant, which may have limited its efficiency.

Phosphate fertilizer applied in 1986 continued to have a significant residual effect on crop growth in 1987 and 1988 (Table 7). As in the annual application treatments, a positive response to increased planting density was found. Farmers (replicates) were separated on the basis of plant density in fertilized plots into high-density (HD–>5,000 pockets ha^{-1}) and low-density (LD–<5,000 pockets ha^{-1}) subgroups. In 1987, yields in the LD plots averaged 170 kg ha^{-1} lower across all treatments than those of HD fields. In both density ranges, crop response to residual phosphate fertilizer averaged 190–200 kg grain ha^{-1}. No significant difference was found between P sources or methods of P application in terms of residual fertilizer response. Similar, though less pronounced, trends were noted in 1988. Though no significant residual response to fertilizer was found in the LD plots, yields in the HD plots averaged 100 kg grain ha^{-1} higher than controls. A significant residual effect, in terms of increasing plant density, and therefore yield, was also found for 2 years after phosphate application though no such effect was noted with nitrogen. These residual effects must be considered when determining economically optimal fertilizer use strategies for the farmer in Niger.

A significant effect of fertilizer use on plant density at harvest was noted in all years (Table 8). Even though each farmer planted at the same density in the control and fertilized plots, average densities at harvest in 1986 for the fertilized treatments were 49% higher than found in the control plots. Similar trends were noted in 1987 and 1988, suggesting that P fertilizer use had the additional effect of increasing plant density at harvest by increasing the survival rate of plants. These results illustrate the role that fertilizer use can have on early crop development and crop survival. Fertilizer promotes rapid early shoot and root growth and thus enables the plant to

Table 8. Effect of fertilizer application on crop density at harvest

Treatment	1986	1987	1987 (residual)	1988	1988 (residual)
	($\times$1,000 pockets ha^{-1})				
Control	3.39	4.33	4.33	2.19	2.19
SSP broadcast	4.65	6.17	5.43	4.21	3.19
SSP + N broadcast	4.58	6.21	5.65	4.10	2.80
SSP + N hill placed	5.09	6.60	5.62	5.38	3.41
PAPR + N broadcast	5.85	6.17	5.85	5.47	4.21
Average (fertilized plots)	5.04	6.29	5.63	4.79	3.40
LSD$_{0.05}$	1.37	1.28	1.10	1.01	0.95

better withstand early drought stress. In addition, improved vigor reduces the extent of injury caused by moving soil in the sandstorms that may precede major rainfall events in the Sahel. Fertilizer application, therefore, not only increased yield/pocket but also had the additional benefit of increasing the survival rate of the crop. The beneficial effect of fertilizer would thus be even greater than that shown in Figure 1 if consideration were given to the fact that fertilizer use also tended to positively affect crop density.

Economic analysis

An economic analysis of the data is limited by the use of only single rates of P and N in the study and the fact that response functions are determined only by density and its interactions with fertilizer. However, within these limits, some interesting trends can be noted.

It is evident that fertilizer use efficiency, and therefore the profitability of its use in farmers' fields, depends significantly on crop density, which, in turn, determines the millet response. Once this is set, the profit realized by the farmer depends on two ratios: the ratio of the value of the additional grain produced to the cost of the fertilizer inputs necessary to achieve this yield (value : cost ratio) and the ratio of the costs of a kilogram of fertilizer to the value of a kilogram of millet (price ratio). These ratios will vary with government pricing policy and market prices. Based on the yield model described in Equation 1 and on the density reduction without fertilizer, Figure 2 describes how the value : cost ratio for fertilizer use depends on both the price ratio and planting density. A value : cost ratio of 2.0 has

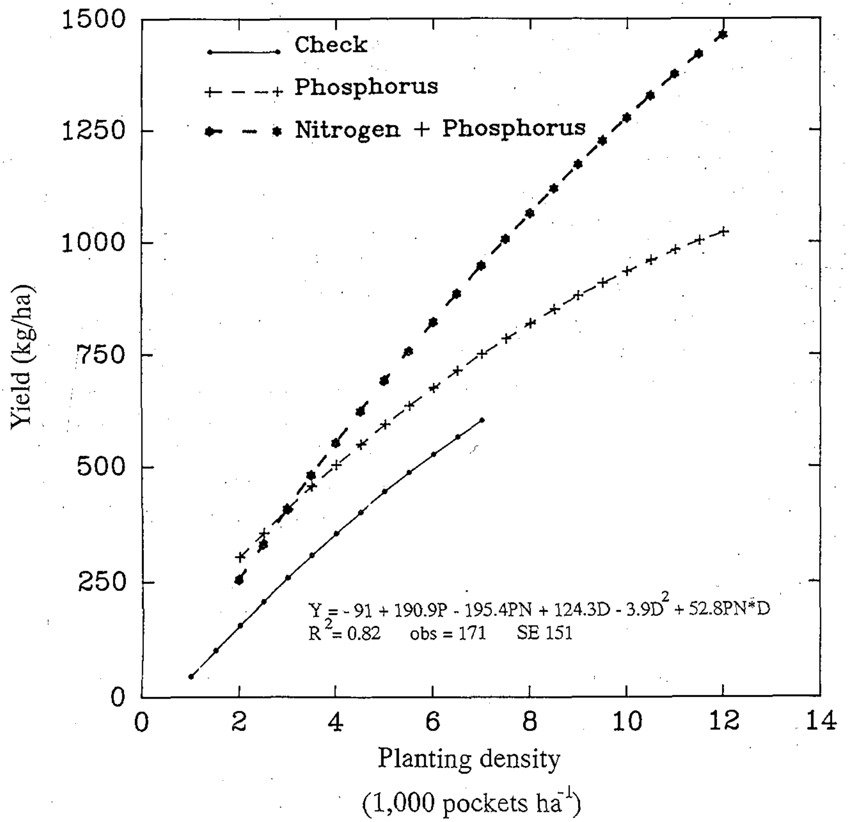

Fig. 1. Effect of plant density and fertilizer use options on millet yield in farmers' fields where Y = grain yield kg ha^{-1}, D = plant density (10^3 pockets ha^{-1}) P and PN represent P fertilizer only and P + N fertilizer codes with values of 1 and 0 represent for treatments with and without fertilizer, respectively.

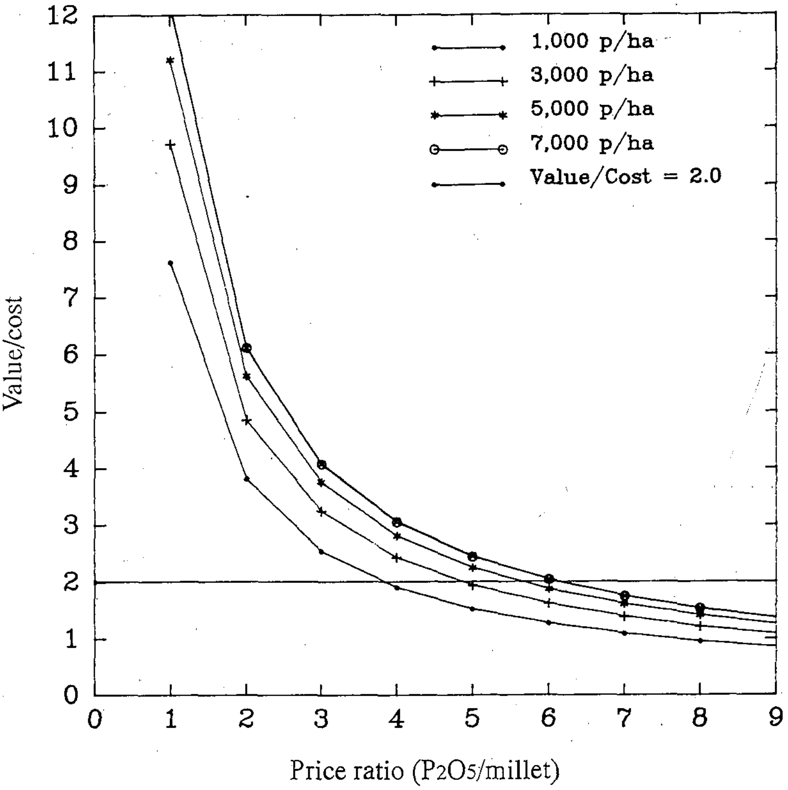

Fig. 2. Effect of price ratio and planting density on value:cost ratio where farmers use only P fertilizer at 30 kg P_2O_5 ha^{-1}.

been chosen by FAO as the economic limit above which a farmer will likely adopt a crop management practice [FAO, 1975]. In such a case a farmer would achieve a return on a fertilizer investment of 100%.

When millet prices are high and/or P fertilizer is inexpensive (price ratio of 3.5 or less), the model indicates that use of 30 kg P_2O_5 is profitable at any density in excess of 1,000 pockets ha^{-1} and would result in a value:cost greater than 2.0. As the price ratio increases, profitability of P use is limited and when it reaches 6.0, even very high densities will not make P fertilizer by itself a viable option.

Because phosphate plus nitrogen is more expensive than phosphate alone and the effect of N is not as strong as that of P at low density, a very favorable P + N pricing must be in effect before their use at low density will result in acceptable value:cost ratios. Thus, the farmer must use high densities to maximize the benefit of his inputs. Figure 3 indicates that in no case will P + N (30 kg ha^{-1} as P_2O_5 and N) be profitable at a density of 1,000 pockets ha^{-1} and only at 3,000 pockets ha^{-1} will P + N fertilizer show profitability at a price ratio of 4 or lower. However, as the price ratio increases to 10, P + N fertilizer use can still exceed a value:cost of 2.0 if densities are high enough.

Summary

The data from these experiments in farmers' fields of Niger illustrate the large yield benefits that a farmer can achieve from N and P fertilizer use. However, unless an adequate planting density is used, maximum benefit from fertilizer use will not be realized. Though the farmer may associate a greater chance of crop failure with such planting rates, Bationo et al. [1990b] found negligible negative risk associated with planting densities of 10,000 pockets ha^{-1}, even in years of severe drought. On the basis of these experiments, it is recommended that the introduction of mineral fertilizer-use packages to the farmer

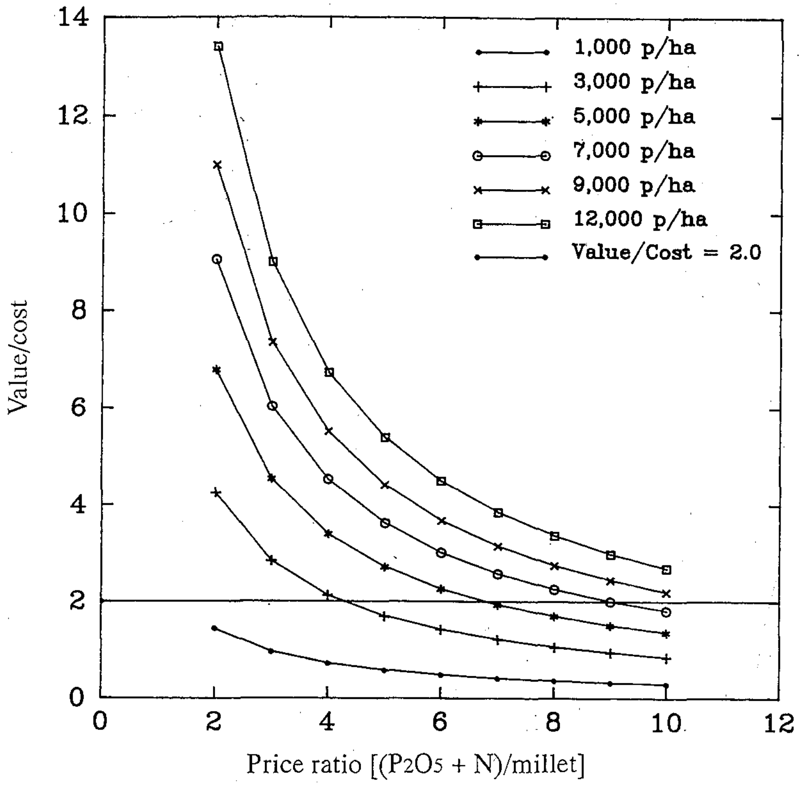

Fig. 3. Effect of price ratio and planting density on value:cost ratio where farmers use both P (30 kg P_2O_5 ha^{-1}) and nitrogen (30 kg N ha^{-1}) fertilizers.

include a strong emphasis on the need to use planting densities of at least 10,000 pockets ha^{-1}. If farmers are unwilling or unable to change their planting practices because of other socioeconomic pressures and prefer to retain their low densities, the value of N in the fertilizer package becomes limited, and its use will probably not be economically feasible.

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