Effects of NPK Fertilizer Combinations on Yield and Nitrogen Balance in Sorghum or Pigeonpea on a Vertisol in the Semi-Arid Tropics

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A long-term experiment was carried out on a Vertisol from 1986 to 1992 to examine the combined effects of NPK fertilizers on yield using sorghum (*Sorghum bicolor* L. Moench cv. CSH 5) and short-duration pigeonpea (*Cajanus cajan* L. Millsp. cv. ICPL 87). The fertilizer treatments were as follows: 0 (no fertilization), N (150 kg N ha^{-1}), P (65.5 kg P_2O_5 ha^{-1}), K (124.5 kg K_2O ha^{-1}), and all possible combinations (NP, NK, PK, and NPK). In this study we continued this experiment during the period 1993 to 1994 and analyzed the crop yield response to fertilizers and the N balance. The amount of N derived from the atmosphere and fertilizer was estimated by the ^{15}N natural abundance method and ^{15}N isotope dilution method, respectively. A combined application of N and P fertilizers gave the highest grain yield for the two crops under the 8th and 9th continuous croppings, unlike the application of K fertilizer. The values of total N for the two crops were significantly higher in the NP and NPK plots. These crops took up N mainly from soil. There was a significant positive relationship between the uptake of N_{dff} and N_{dfs} by each crop. Pigeonpea or sorghum took up more N from the soil in the N fertilizer plots than in the plots without N, suggesting that soil N fertility was enhanced and the amount of N supplied from soil increased in the plots with consecutive application of N fertilizer for 7 y. Even pigeonpea, which fixes atmospheric N inherently, needed N fertilizer to achieve high grain yield, suggesting that N fixation by the nodules was not always sufficient to meet the N requirements of the crop under these conditions. Although fertilizer N exerted a beneficial effect on plant growth and yield in the two crops, the values of fertilizer N recovery (FNR) by the two crops were considerably low. Therefore, it is suggested that the development of N fertilizer management which could maximize FNR of each crop should be promoted.

Key Words: **fertilizer, ^{15}N natural abundance, nitrogen, pigeonpea, sorghum.**

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Fertilizer management is important to obtain high grain yield in upland crops cultivated on Vertisols. Burford et al. (1989) recommended the application of N and P but not that of K on Vertisols since there was a large amount of available K for crops in such soils. Meanwhile, crops after legume cultivation needed less N fertilizer on Vertisols (Wani et al. 1995). Thus, the response of crop yield to fertilizers could be affected by the amount of available nutrients in soil and previous crops. In the semi-arid tropics (SAT), sorghum and pigeonpea are usually cultivated continuously since they are staple food and cash crop, respectively (ICRISAT 1994). To achieve high sustainable yield in the SAT, it is important to evaluate the yield response to fertilizers under continuous cropping for effective fertilizer management on Vertisols. Although many studies have been carried out on the effect of fertilizers on crop yield in the SAT (Kumar Rao and Dart 1987; Bhandari et al. 1989), few studies were carried out from these view points. In the current study, we used the same crops and the field established under for continuous cropping and different NPK combinations for the past 7 y and monitored the response of yield to fertilizer application and the N balance in the two crops for the following 2 y.

MATERIALS AND METHODS

The experiment was conducted at the same site on a deep Vertisol at ICRISAT Asia Center, India in the rainy season from 1986 to 1992. The initial characteristics of the soil in the experimental area were as follows: pH, 8.6 (1 : 2 soil/water ratio); inorganic N content, 24.7 mg kg^{-1} soil; available P, 8.6 mg kg^{-1} soil; and exchangeable K, 298 mg kg^{-1} soil. The experimental design consisted of a split-plot with three replications. The main plots were allocated to either sorghum (*Sorghum bicolor* L. Moench cv. CSH 5) or short-duration pigeonpea (*Cajanus cajan* L. Millsp. cv. ICPL 87). Within each main plot there were eight subplots for fertilizer treatments, 0 (no fertilization), N (150 N kg ha^{-1} as urea), P (65.5 kg P_2O_5 ha^{-1} as single superphosphate), K (124.5 kg K_2O ha^{-1} as potassium chloride), and all possible combinations (i.e., NP, NK, PK, and NPK treatments). Each subplot had been continuously cultivated with pigeonpea or sorghum during the 7-y periods (1986 to 1992) except in 1989 when half of each subplot was allocated to either crop and subjected to the same fertilizer treatment for 7 consecutive y. The size of each subplot was 6 m×4 m, consisting of 8 ridges 75 cm in width. Fertilizers were broadcasted to the soil surface and incorporated into the soil up to a 20 cm depth by disc ploughing before sowing, unlike lime application. Seeds of pigeonpea were sown 10 cm apart in two rows on either side of the ridges at a spacing of 75 cm (i.e., 10 cm×37.5 cm), while those of sorghum were sown 10 cm apart in a ridge at a spacing of 75 cm on June 29, 1993 and on June 14, 1994. At about 2 weeks after sowing, emerged plants were thinned to one plant per hill. Supplementary irrigation was applied when required. The crops were protected from pod borer (*Helicoverpa assulta* Guenee) infestation by spraying of Endosulphan and from Phytophthora blight (*Phytophthora drechsleri* Tucker F. sp. *cajani* Kannaiyan et al.) by spraying of Benomyl.

Soil monoliths were taken to determine the nodule number and nodule activity of pigeonpea by the acetylene reduction assay at flowering in the latest plots (92 d after sowing (DAS)) in 1994. There was a difference of 7 d between the earliest and latest flowering. Soil monoliths (37.5 cm×10 cm×30 cm depth) were carefully taken from the middle ridge to middle row in all the subplots. Roots with nodules were immediately washed to remove soil and placed into incubation bottles. After the addition of acetylene (10% v/v) into the bottles, they were incubated at 30°C for 1 h. Ethylene production was measured with a gas chromatograph fitted with a FID detector (F33 type, Perkin-Elmer Limited, UK).

The crops were harvested at maturity on October 22, 1993 and October 13, 1994 for sorghum and on November 11 (harvest of crops from first flush flowers) and 30 (harvest of crops from second flush flowers), 1993 and on November 9 and 28, 1994 for pigeonpea. The dry weight of the samples was determined after oven-drying at 70°C, and a portion of the ground material was used for N analysis.

Total N content was determined based on the color associated with indophenol production (Chaykin 1969). For the analysis of ^{15}N natural abundance, N_2 gas from digested samples was introduced into a mass spectrometer (RM-I-2, Hitachi, for the ^{15}N-enrichment samples and Finnigan Mat 251 for natural ^{15}N abundance) to measure the ^{15}N abundance in the samples. Detailed procedures for ^{15}N natural abundance analysis and the estimation of the amount of N derived from air (N_{dfa}) have been described elsewhere (Tobita et al. 1994). Each plot with N-fertilizer contained two 0.75 m×0.4 m microplots for ^{15}N balance determination in 1994. The microplots were demarcated at the center of the N-fertilizer plots. Microplots were fertilized with labeled ammonium sulphate (10.09 atom% excess). Plants were harvested at ground level from the microplot, dried to each a constant weight at 70°C, and analyzed for total N and ^{15}N contents. Samples of soil cultivated with pigeonpea were collected at intervals of 30 cm depth down to 90 cm with a 0.05 m diameter auger at 94 DAS in 1994. The collected soil samples were air-dried and passed through a 2 mm mesh sieve. Nitrate-N content in soil was estimated by extracting soil with 2 M KCl after shaking for 1 h. The soil extracts were filtered through Whatman No. 1 filter paper and aliquots of KCl extracts were analyzed for nitrate-N by distillation of the aliquot in a micro-Kjeldahl apparatus using MgO and Devarda's alloy (Jackson 1973).

In this area, the average rainfall is 784 mm and the rainfall is mainly distributed at the onset of the rainy season (June–November). Usually, sorghum and pigeonpea are sown and harvested during the rainy season. Farmers apply less fertilizer compared to the amount used in our experiment. Heading of sorghum occurred in the middle of August and flowering of pigeonpea occurred at the beginning of September, as usual.

RESULTS

1. Shoot dry matter and grain yield

The shoot dry matter (SDM) at harvest and grain yield of sorghum or pigeonpea in the NP and NPK plots were significantly higher than those in the other plots in 1993 and 1994 (Fig. 1a and b, Table 1). A single application of N or P did not contribute to a significant increase in SDM at harvest and grain yield. However, a combined application of N and P (i.e., NP and NPK) resulted in the highest grain yield for sorghum and pigeonpea. The effect of K application on the SDM at harvest and grain yield for both crops was not significant.

2. Nitrogen uptake and nitrogen balance in shoot

Amount of N taken up by sorghum or pigeonpea at harvest in the NP and NPK plots was significantly higher than that in the other plots (Tables 2 and 3). The fractional contribution of N derived from soil ($\%N_{dfs}$) and the amount of N derived from soil (N_{dfs}) for the two crops were higher than the fractional contribution of N derived from fertilizer ($\%N_{dff}$) and the amount of N derived from fertilizer (N_{dff}), respectively. Pigeonpea or sorghum in the N fertilizer plots took up more N from the soil than in the plots without N.

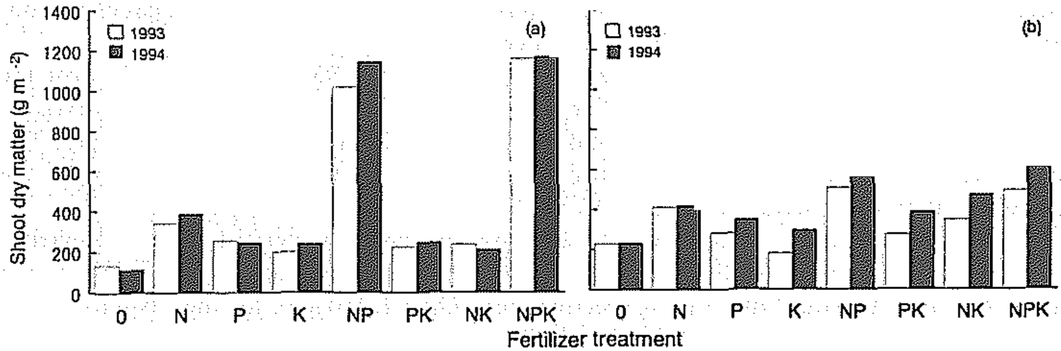

Fig. 1. Effects of fertilizer treatments on shoot dry matter in sorghum (a) and pigeonpea (b) at harvest during 1993 and 1994. Vertical bars represent standard error and show significant difference at 1% level.

Table 1. Grain yield of sorghum and pigeonpea during the period 1993 and 1994.

Treatment	Sorghum ($g\ m^{-2}$)		Pigeonpea ($g\ m^{-2}$)	
	1993	1994	1993	1994
0	39	34	58	62
N	120	132	112	80
P	82	80	74	73
K	66	80	44	57
NP	365	376	131	115
PK	57	86	76	73
NK	68	74	76	97
NPK	407	349	142	140
SE(±)	13**	20**	10**	9**

** $p<0.01$.

Table 2. Total nitrogen (TN), fractional contribution, and amount of N derived from fertilizer (%N_{dff} in relation to N_{dff}), soil (%N_{dfs} in relation to N_{dfs}), and fertilizer N recovery (FNR) in sorghum at harvest in 1994.

Treatment	TN ($g\ m^{-2}$)	%N_{dff} (%)	N_{dff} ($g\ m^{-2}$)	%N_{dfs} (%)	N_{dfs} ($g\ m^{-2}$)	FNR (%)
0	0.7	0	0	100	0.7	0
N	3.8	12.1	0.4	87.9	3.3	2.7
P	1.8	0	0	100	1.8	0
K	1.5	0	0	100	1.5	0
NP	12.0	13.4	1.6	86.6	10.4	10.7
PK	1.6	0	0	100	1.6	0
NK	2.2	9.8	0.2	90.2	2.0	1.3
NPK	13.3	11.2	1.5	88.8	11.8	10.0
SE(±)	1.0**	0.6**	0.1**	0.6**	0.9**	0.7**

** $p<0.01$.

The values of fertilizer N recovery (FNR) by the two crops in the NP and NPK plots were significantly higher than those in the other plots. There was a significant positive relationship between the amount of N_{dff} and N_{dfs} taken up by sorghum or pigeonpea, respectively

Table 3. Total nitrogen (TN), fractional contribution, and amount of N derived from fertilizer (%N_{dff} in relation to N_{dff}), from air (%N_{dfa} in relation to N_{dfa}), soil (%N_{dfs} in relation to N_{dfs}), and fertilizer N recovery (FNR) in pigeonpea at harvest in 1994.

Treatment	TN ($g\ m^{-2}$)	%N_{dff} (%)	N_{dff} ($g\ m^{-2}$)	%N_{dfa} (%)	N_{dfa} ($g\ m^{-2}$)	%N_{dfs} (%)	N_{dfs} ($g\ m^{-2}$)	FNR (%)
0	4.8	0	0	57.8	2.8	42.2	2.0	0
N	7.9	8.6	0.7	13.9	1.1	77.6	6.1	4.7
P	6.5	0	0	64.6	4.1	35.4	2.3	0
K	5.2	0	0	52.2	2.8	47.8	2.4	0
NP	10.2	10.2	1.0	19.8	2.1	70.0	7.0	6.7
PK	8.4	0	0	54.6	4.5	45.4	3.9	0
NK	8.0	9.4	0.8	20.3	1.7	70.4	5.6	5.3
NPK	10.5	11.1	1.2	19.8	2.1	69.1	7.2	8.0
SE(±)	0.8**	1.1**	0.1**	5.6**	0.6**	6.1**	0.6**	0.7**

** $p<0.01$.

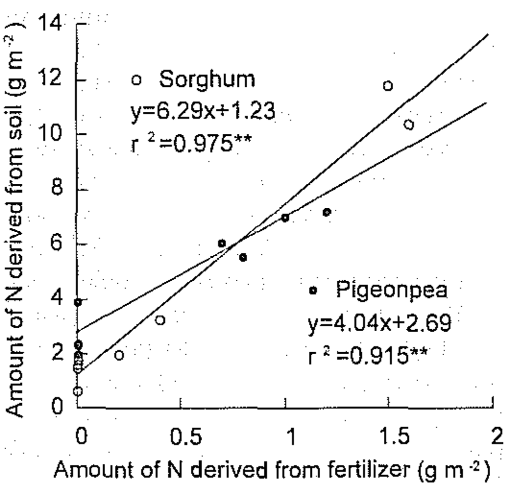

Fig. 2. Relationship between the amount of nitrogen derived from fertilizer and nitrogen derived from soil taken up by sorghum and pigeonpea. **$p<0.01$.

Table 4. Nodule number (NN), nodule fresh weight (NFW), and acetylene reduction activity (ARA) in pigeonpea at 92 d after sowing in 1994.

Treatment	NN ($plant^{-1}$)	NFW ($g\ plant^{-1}$)	ARA ($\mu mol\ plant^{-1}\ h^{-1}$)
0	34	1.08	0.43
N	28	0.52	0.22
P	37	1.68	0.83
K	41	0.91	0.59
NP	30	0.54	0.32
PK	43	1.88	0.74
NK	36	0.48	0.22
NPK	56	0.97	0.37
SE(±)	7^{NS}	0.22**	0.12*

* $p<0.05$, ** $p<0.01$, ^{NS} not significant.

(Fig. 2). On the other hand, the amount of N_{dfa} taken up by pigeonpea in the 0, P, K, and PK plots was significantly higher than that in the other plots.

Table 5. Nitrate-N content in soil layers at 0-30, 30-60, and 60-90 cm depths under pigeonpea cultivation 94 d after sowing in 1994.

Treatment	Nitrate-N content (mg kg^{-1})		
	0-30 cm	30-60 cm	60-90 cm
0	23.2	27.8	16.2
N	37.2	53.2	38.6
P	34.1	19.8	19.2
K	26.7	20.8	25.6
NP	43.8	56.8	52.6
PK	28.2	22.0	24.2
NK	39.9	68.6	36.8
NPK	43.2	67.8	33.0
SE(±)	6.44^{NS}	11.2*	4.07**

* $p<0.05$, ** $p<0.01$, ^{NS} not significant.

3. Nodule number, nodule fresh weight, acetylene reduction activity, and soil chemical characteristics

There were no significant differences in the nodule number in pigeonpea among the treatments (Table 4). The nodule fresh weight and the acetylene reduction activity (ARA) of the nodules for pigeonpea in the P and PK plots were significantly higher than those in the other plots at 92 DAS in 1994. There was a significant positive relationship between the ARA of the nodules and the nodule fresh weight ($r^2=0.848$**), but not the nodule number ($r^2=0.075$). The amount of N_{dfa} taken up was related to the ARA of the nodules ($r^2=0.905$**). The nitrate-N content in the topsoil in the N fertilizer plots was not higher than that in the absence of N fertilizer treatments at 94 DAS (Table 5). However, the nitrate-N content at a soil depth below 0.3 m was significantly higher in the N fertilizer plots than in the plots without N.

DISCUSSION

High yields of the two crops under the 8th and 9th continuous croppings and consecutive fertilizer applications were recorded in the NP and NPK plots (Table 1). Heading of sorghum without N and P applications was delayed from 25 to 39 d. It was reported that the application of N and P affected the yield components like primary and secondary branching, number of pods per plant and grain yield per plant in pigeonpea (Bisen et al. 1983). Therefore, sorghum and pigeonpea required the application of both N and P to achieve a high grain yield on a Vertisol in the SAT in this experiment, while K application was not essential. The same results were obtained under the 5th, 6th, and 7th continuous croppings in previous experiments (Matsunaga et al. unpublished). The results of yield responses to fertilizer application agreed well with the results obtained by Bhandari et al.(1989) in pigeonpea and Sahrawat (1988) in sorghum. The response to N and P applications may be attributed to the low availability of N due to leaching by heavy rain at the onset of the rainy season and of P due to immobilization in the soil of the experimental site. Further studies on the estimation of N and P dynamics in the present soil should be carried out.

The yield advantage in sorghum or pigeonpea was ascribed to the high N uptake at harvest (Tables 2 and 3). The values of total N for the two crops were significantly higher in the NP and NPK plots. These crops accumulated large amounts of N from soil. There were significant relationships between the uptake of N_{dff} and N_{dfs} by sorghum and pigeonpea, respectively (Fig. 2). The value of the regression intercept at 0 value of the amount of N_{dff} taken up by pigeonpea was higher than that in sorghum since pigeonpea could grow without N fertilizer due to biological N fixation (BNF). The relationship observed was in good agreement with the results reported by Olfs and Werner (1994). The uptake of N_{dfs} by sorghum or pigeonpea in the N fertilizer plots was higher than that in the plots without N (Tables 2 and 3, Fig. 2). The increase in the uptake of N_{dff} and N_{dfs} could be associated with root growth. It was estimated that soil N fertility was enhanced and N supply from soil increased during the 7-y period.

Liljeroth et al. (1994) reported that a large amount of microbial biomass was incorporated due to the release of carbon from crop roots in the N fertilizer plots. In sorghum, the uptake of N_{dfs} in the NP and NPK plots was higher than that in the N plot (Table 2). It is considered that microbial biomass increased due to the large root mass associated with P application (Sahrawat 1988) and enhanced soil N fertility. Further studies on the quantification of the changes in the soil microbial biomass C and mineralizable and total-N in the soil should be carried out to analyze soil N fertility.

Although the amount of N_{dfa} taken up by pigeonpea surpassed that of N_{dfs} in the P and PK plots, the amount was not sufficient to meet the N requirement of the crop to achieve a high yield. The values of ARA of the nodules and the nodule fresh weight in the P and PK plots were significantly higher than those in the N fertilizer plots due to the low content of nitrate-N in the subsoil (Table 5). The values of ARA of the nodules were within the range of those reported by Matsunaga et al. (1994). Although the low nitrate concentration in the soil resulted in a high nodule fresh weight (Streeter 1986) and enhancement of BNF (Peoples et al. 1995), continuous cropping and environmental factors affected the nodulation and ARA of pigeonpea. The low nodule mass and ARA of pigeonpea in Vertisols may be due to nodule damage caused by *Rivellia* sp. (Kumar Rao and Sithanantham 1989) and soil saturation with water during the rainy season (Okada et al. 1991). Therefore, further increase in the amount of N_{dfa} taken up by pigeonpea under the present conditions could be difficult due to these factors.

Although fertilizer N exerted a beneficial effect on plant growth and yield in the two crops, the values of FNR for the two crops were considerably low (Tables 2 and 3). This phenomenon was attributed to the large extent of leaching losses by heavy rain at the seedling stage and insufficient plant growth due to the build-up of soil-borne diseases and insect pests during continuous cropping. Since fertilizer is valuable in the SAT, the development of N fertilizer management (i.e. using slow-acting fertilizers or split applications) which could maximize FNR of each crop should be promoted. Adu-Gyamfi et al. (1997) reported that FNR by sorghum with basal application of N which amounted to 15% increased to 32% where N application was delayed.

In conclusion, it became evident that sorghum and pigeonpea needed both N and P fertilizers to achieve high grain yield on a Vertisol in the SAT in this experiment. The yield advantage of sorghum or pigeonpea was ascribed to the high N uptake up to harvest. These crops accumulated large amounts of N from soil. There was a significant positive relationship between the uptake of N_{dff} and N_{dfs} by each crop. Pigeonpea or sorghum took up more N from the soil in the N fertilizer plots than in the plots without N. Even pigeonpea, which fixes atmospheric N inherently, needed N fertilizer to achieve high grain yield, suggesting that N fixation by the nodules was not always sufficient to meet the N requirements of the crop under these conditions. In the current experiment, pigeonpea may require fertilizer N for seedling growth as starter-N. Although fertilizer N exerted a beneficial effect on plant growth and yield in the two crops, the values of fertilizer N recovery (FNR) by the two crops were considerably low, suggesting that the development of N fertilizer management which could maximize FNR of each crop should be promoted.

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