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Timing of N fertilization on N_2 fixation, N recovery and soil profile nitrate

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Abstract

Cropping systems and fertilizer management strategies that effectively use applied nitrogen (N) are important in reducing costs of N inputs. We examined the effect of time of N application on dry matter (DM) and grain yield (GY), N accumulation, the N budget in crop from soil, fertilizer and atmosphere, and the fertilizer N use efficiency (estimated by the conventional difference method, and the direct ^{15}N recovery by the crops), in a sorghum/pigeonpea intercropping system on an Alfisol (Ferric Luvisols (FAO); or Udic Rhodustalf (USDA) in India. Fertilizer N was applied at planting (basal) and at 40 days after sowing (delayed). Nitrogen was applied only to the sorghum rows in the intercropping treatment. Nitrogen derived from air (N_{dfa}) was estimated by the ^{15}N natural abundance method, and N derived from fertilizer (N_{dff}) was estimated by the ^{15}N isotope dilution method.

Delaying N fertilization till 40 days after sowing (DAS), rather than applying at sowing increased DM and GY of the sorghum, but not of pigeonpea. Delaying N fertilization to sorghum for 40 days significantly ($p<0.001$) increased ^{15}N recovery in shoot from 15 to 32% in sole crop, and from 10 to 32% in intercrop. Similarly, there was a significant ($p<0.001$) increase in N recovery (by the difference method) from 43 to 59% in sole crop and from 28 to 71 % in intercrop sorghum. Fertilizer N recovery by sole crop pigeonpea (14%) was higher than intercrop pigeonpea (2–4%). Pigeonpea fixed between 120–170 kg ha^{-1} of atmospheric N throughout the cropping season. Although there was a marked difference in nitrate-N ($N0_3$-N) concentrations between basal and delayed treatments at planting, no difference was observed in $N0_3$-N concentrations in soil solution between the treatments at 40 DAS. Our data on N accumulation by plants showed that the rate of N depletion or disappearance from the soil solution was 2–3 times faster than N accumulation by plants, suggesting that an appreciable amount of $N0_3$-N would disappear from soil solution in the top soil without being utilized by crops during the initial growth stage.

Introduction

Pigeonpea and sorghum are important food grain crops in the semi-arid tropical areas in India, and eastern Africa. Apart from the edible grains, sorghum is used for fodder whereas the stems of pigeonpea are used as firewood. Pigeonpea is grown as an intercrop with a combination of cereal crops like sorghum and pearl millet, although a combination with other legumes like groundnut and cowpea is becoming popular probably because of the economic value of legumes (Gadhia et al., 1993; Katayama et al., 1995; Venkateswarlu & Subramaniam, 1990.)

Despite pigeonpea and sorghum generally being grown under inter-or mixed cropping systems, studies on fertilizer use efficiency (FUE) have mainly focused on sole cropping systems. Application of N fertilizer to legumes decreases its dependency on N_2 fixation, therefore most farmers assume that fertilizer N application to intercropping system may be antagonistic instead of synergetic. The N requirements of sorghum when grown as sole crop are reported to be higher than when grown as intercrop (Soundarajan, 1978). However, higher nutrient uptake by pigeonpea in a pigeonpea/maize (Dalal, 1974), pigeonpea/mungbean (Srinivasan & Ahalwat, 1984) and pigeonpea/sorghum (Tobita et al., 1994) as compared to sole-cropped pigeonpea have also been reported. Venkateswarlu et al. (1981) reported that in a sorghum/pigeonpea intercrop, 80 kg N ha^{-1} was optimal, whereas Adu-Gyamfi et al. (1996), Naraian et al. (1980) recommended a moderate dose of N (25–30 kg N ha^{-1})

Adu-Gyamfi et al. (1996) reported that there is an appreciable accumulation of soil $N0_3$-N (50∼80 kg N ha^{-1}) prior to planting. The ability of sorghum to utilize this native soil nitrate at the early vegetative stage would help deplete the soil N concentration around pigeonpea roots and increase its dependency on N_2 fixation. Thus, timing of fertilization to intercropping is very important in the semi-arid tropics. In addition, application of N to pigeonpea during the pod filling stage (where the N_2 fixing ability is low and N requirements are high) could help increase grain yield and the over all productivity of the system (Kumar Rao et al., 1995).

Medium duration pigeonpea is compatible with short duration sorghum (land equivalent ratio varying from 1.2∼1.8) as intercrops because of the difference in maturity period (Ali, 1990; Gupta & Sharma, 1984). We examined the effect of time of N application on dry matter yield, N accumulation in plant, the N budget in crop from soil, fertilizer and atmosphere, and the FUE (^{15}N recovery by the crops) in a sorghum/pigeonpea intercropping on an Alfisol in India under rainfed conditions.

Materials and methods

Crop cultivation and management

The study was conducted during the 1993 rainy season on a medium-deep Alfisol (Ferric Luvisols (FAO); Udic Rhodustalf (USDA) at ICRISAT Asia Center, Patancheru (17°38′N, 78°21′E) India. The experimental site had been left fallow with weeds for 3–4 years. The surface 20-cm soil depth had an average available moisture storage capacity of about 100 mm, pH (H_2O) 6.2, mineral N 40 mg kg^{-1}, and available P (Bray II) 10 mg kg^{-1}. The experiment was a 4 × 3 factorial, set out in a split-plot design with three replicates. Main treatments were four cropping systems namely (i) sole crop sorghum (ii) sole crop pigeonpea (iii) intercrop sorghum/pigeonpea and (iv) a bare fallow treatment (to serve as a control plot for monitoring N dynamics in the soil), were randomly assigned to the main plots. The sub-plot treatments were (i) no N fertilizer applied (N0), (ii) N application of 50 kg N ha^{-1} at planting (basal) and (iii) N application of 50 kg N ha^{-1} at 40 days after sowing (delayed). All the N fertilizer was applied by opening the furrows and banding at 5–8 cm depth. In the intercropping treatment (mixture of sorghum and pigeonpea plots), N was applied only to sorghum rows. Phosphorus was applied basally broadcast to all the experimental plots at the rate of 20 kg ha^{-1} as single superphosphate.

Medium-duration pigeonpea (*Cajanus cajan* (L) Moench) cultivar ICP 1-6., and grain sorghum (*Sorghum bicolor* (L) Moench) hybrid CSH 5, were sown on 19 June 1993. The inter-row spacing was 60 cm. The intra-row spacing differed among the cropping systems, with 15 cm for sole crop sorghum, 30 cm for sole crop pigeonpea, and 10 cm for both crops in the intercropping, which had a 2:1 (sorghum:pigeonpea) row proportion. This arrangement gave an identical number of plants per unit area for each component in the sole and intercropping systems. The experiment consisted of a total of 36 sub- plots; each measuring 7.8 × 5.4 m. Two seeds of pigeonpea and 5 seeds of sorghum were sown at precisely the required distance. Seedlings were thinned to one per hill 8 days after germination. All sowing and fertilizer application were done by hand in open furrows between 10 cm ridges. Pigeonpea plants were well nodulated with native Rhizobium which was abundant in the soil. For ^{15}N application, microplots measuring 90 × 90 cm for sole crop pigeonpea, 45 × 90 cm for sole crop sorghum, 50 × 90 cm for intercrop, and 45 × 60 cm for the bare fallow plots, were demarcated with iron pegs. The ^{15}N-labelled urea (30 atom% excess, Shoko Co. Ltd., Japan) was applied by banding to crop rows in all microplots, at the same time and rate as for the surrounding ^{14}N urea. Plots were irrigated by overhead sprinkler at 7 and 11 DAS, and by furrow irrigation during the flowering (75–80 DAS) stage. In addition to the total rainfall of 759 mm in 1993, plots received additional amount of 100 mm during the experimental period. Insecticides and fungicides were sprayed as necessary to minimize damage caused by Fusarium wilt and pod borer (*Helicoverpa armigera*). Weeds were controlled by hand during the experimental period.

Installation of ceramic porous cups for soil solution sampling

Two days before planting, porous ceramic cups (0.7 cm diameter and 6 cm height) were embedded at depths of 0–15, 15–30, and 45–60 cm in all plots (including the bare-fallow). The ceramic cups were installed by drilling a hole with a 0.75-cm (outside diameter) soil auger to the desired soil depths. Three porous cups (one for each soil depth) were installed at 4–11 cm (0–15), 20–26 cm (15–30) and 50–56 cm (45–60) for all sole crop and the bare fallow plots, whereas 6 cups (3 cups each for sorghum and pigeonpea) were installed in the intercrop plots. Sieved soil from the auger was poured back and tampered down slightly to ensure good hydraulic contact with the ceramic cups. Soil water (2–5 ml) was collected at 3 days interval (depending on the soil moisture) from the porous cups by suction for 2 hr using a 50 ml gas-tight plastic syringe. The soil solution was stored in small air tight bottles and was either analysed immediately, or kept at −20 °C until analysis.

Soil sampling for KCl extraction

Soil samples were collected weekly (from an area close to porous cups) using the core method. At each sampling, a long cylindrical tube with an inner diameter of 2 cm was hammered vertically into the soil to a 60 cm depth. The core samples were sectioned into segments of 0–15, 15–30 and 45–60 cm. The fresh soil samples were stored in plastic bags and placed into an ice cooler and quickly transferred to the laboratory. Upon arrival, the samples were immediately extracted with 1 *M* KCl (1:5 w/v). The soil solution extracts were kept at −4 °C till analysis.

Crop harvest

Shoot samples were taken from a 0.8 m^2 area from each plot at 28, 40, and 78 DAS. At maturity (110 days for sorghum and 210 days for pigeonpea), an area of 4 rows by 4 m (9.6 m^2) were harvested to estimate total dry weight and grain yields. For growth analysis, plant samples were separated into leaves (lamina), stems (including petioles) and reproductive organs depending on the growth stage dried at 70 °C for 48 hr and weighed. Leaf area was measured from sub-sample of leaves using LICOR LI 3100 leaf area meter. Leaf area index (LAI) was calculated as the ratio of total area to the ground area. The land equivalent ratio (LER) and the area time equivalent ratio (ATER) for grain and total dry matter yield were used to evaluate the biological efficiency of the intercropping system relative to sole cropping, and were calculated according to the method of (Hiebsch & McCollum, 1987; Mead & Willey, 1980).

$$\mathrm{LER} = (\mathrm{Y_{sp}}/\mathrm{Y_{ss}}) + (\mathrm{Y_{ps}}/\mathrm{Y_{pp}})$$

$$\mathrm{ATER} = [(\mathrm{Y_{sp}}/\mathrm{Yss})\mathrm{t_s} + (\mathrm{Y_{ps}}/\mathrm{Y_{pp}})\mathrm{t_p}]\mathrm{T}$$

Where Y is the yield per unit area (kg ha^{-1}) Y_{ss}, Y_{pp} are the sole crop yields of sorghum and pigeonpea, respectively,

Y_{sp} and Y_{ps} are the respective yields from the intercrop

Y_{ps}/Y_{ss} and Y_{ps}/Y_{pp} are the relative yields of intercropped sorghum and pigeonpea to sole crop, and t_s, t_p, and T are the durations of sorghum (110 days), pigeonpea (210 days), and the whole cropping system (210 days), respectively.

The chlorophyll content in selected leaves (close to the flag leaf) of sorghum and pigeonpea plants adjacent to where the porous cups have been installed, was monitored weekly using a green chlorophyll meter (SPAD-502, Minolta) previously calibrated.

Nitrogen analysis

Oven-dried shoot samples were ground to pass a 0.4-mm. screen for chemical analysis. Nitrogen in the different plant parts (including fallen leaves) was estimated by the indophenol color formation (Chaykin, 1969) after micro-Kjeldhal digestion with hydrogen peroxide-sulfuric acid mixture. Total N accumulation (kg ha^{-1}) was calculated by multiplying dry matter yield of plant parts and mean N concentrations in plant parts. Nitrate and ammonium concentrations of the soil solution extracted by means of the ceramic porous cups were analyzed colorimetrically, with salicylic acid-sulphuric acid mixture (Cataldo et al., 1975) and phenol-alkaline hypochlorite (Chaykin, 1969), respectively. Nitrate and ammonium-N in the soil extracts were determined by steam distillation. The results were expressed only as $N0_3$-N, since the nitrite-N ($N0_2$ N) concentration was assumed to be negligible.

^{15}N analysis

Four plants of each species were sampled at final harvest from the ^{15}N-treated microplots for the ^{15}N enrichment analysis. Another set of 4 plants were also taken from the surrounding area, which was reasonably far from the microplot for ^{15}N natural abundance (δ^{15}N) analysis. The natural ^{15}N abundance value for pigeonpea grown solely on atmospheric N ($\delta^{15}N_a$ was −2.10‰. This value was used to estimate the % N_{dfa}. Approximately 2 g of finely ground plant samples were digested by the conventional Kjeldhal method with salicylic acid for the conversion of nitrate to ammonium for the ^{15}N enrichment and natural ^{15}N abundance analyses. Nitrogen gas was evolved by mixing the sample solution with NaOBr and purified. The resultant pure N_2 gas was introduced into a mass spectrometer (Finnigan Mat 251) for the measurement of natural abundance in the sample. For the ^{15}N enrichment micro-diffusion for digested samples were carried out and sample solutions containing approximately 0.5 g N l^{-1} was taken with glass capillary tubes (3 mm outer diameter, and 10 mm long). The capillary tubes with samples were introduced into a borosilicate glass, containing 5–10 mg CuO (freshly baked) and CaO (900 °C) granules. The discharge tubes and contents were sealed under vacuum, baked for 1 hr at 560 °C and allowed to cool slowly. The ^{15}N enrichment was determined with an ^{15}N emission spectrometer (Jasco N-150).

Estimation of fertilizer nitrogen use efficiency (FNUE)

The fractional contribution of N in crop derived from fertilizer (%N_{dff}) and fertilizer nitrogen use efficiency (FNNE), were calculated as:

$$\%N_{dff} = (1\text{- } \%\ ^{15}\text{N atom excess in pigeonpea or sorghum}/\ \%\ ^{15}\text{N atom excess in fertilizer}) \times 100$$

$$N_{dff} = N_{total}(\text{kgha}^{-1}) \times \%N_{dff}$$

$$\text{FNUE} = N_{dff}/N_{applied} \times 100$$

Estimation of nitrogen fixation by pigeonpea

The fractional contribution of fixed N derived from air (% N_{dfa}) in pigeonpea was calculated as:

$$\%N_{dfa} = (\delta^{15}N_s - \delta^{15}N_p)/(\delta^{15}N_s - \delta^{15}N_a) \times 100$$

where $\delta^{15}N_s$ and $\delta^{15}N_p$ are the δ^{15}N values for the sorghum and pigeonpea, respectively. Delta $^{15}N_a$ is the value of pigeonpea grown solely on atmospheric N_2 (i.e. -2.1‰).The amount of N symbiotically fixed by pigeonpea (N_{dfa}, kg ha^{-1}) was calculated as:

$$N_{dfa} = N_{total} \times \%N_{dfa}$$

where N_{total} is the total N accumulated by pigeonpea (kg ha^{-1}).

Data analysis

All data were analyzed using GENSTAT 5 Release 3.2 (Copyright 1995, Lawes Agricultural Trust Rothamsted Experimental Station). Analysis of variance technique was used to analyze the data (Gomez & Gomez, 1984).

Results

Plant growth and dry matter yield

Despite a relatively high fertility situation (field left to fallow for 3–4 yr), sorghum responded to added N (Table 1). The response, seen in both grain yield (GY) and dry matter (DM) was greater when the N application was delayed by 40 days. Harvest index (HI) which ranged from 0.32 to 0.39 for sorghum, and from 0.16–0.22 for pigeonpea, was not significantly affected by the N treatments (data not shown). Since both DM and GY were increased, yet HI was not affected, it seems that the effect of added N, was mainly to enhance vegetative growth of plants rather than simply influence grain filling. The response of sorghum to N fertilization was the same in the sole-cropped and intercropped between row of pigeonpea. Pigeonpea, whether as a sole crop or as an intercrop with sorghum, did not respond to applied N, but there was less dry matter production and a lower HI when it was grown in association with sorghum.

The LER and ATER values for DM and GY invariably exceeded unity, indicating considerable advantages for the intercropping system (data not shown). The mean LER values were 1.58 for DM and 1.80 for grain. Similarly, the mean ATER values were greater for GY (1.38) than for DM (1.20). Delaying N fertilization for 40 days to plants slightly increased LER and ATER compared to plots that received N at planting. Sorghum plants that received fertilizer N, whether applied at planting or delayed for 40 days intercepted more light than the plants which received no N fertilizer. Whereas sole-cropped sorghum intercepted more

Table 1. Total dry matter (DM, t ha^{-1}), and grain yield (GY, t ha^{-1}) of sorghum and pigeonpea in sole crop and intercropping systems at harvest

	Sorghum						Pigeonpea					
	DM			GY			DM			GY		
Cropping system	N0[a]	Bas[b]	Del[c]	N0	Bas	Del	N0	Bas	Del	N0	Bas	Del
Sole crop	10.3	14.1	16.1	3.10	4.16	4.58	14.5	18.8	17.2	2.56	2.78	2.43
Intercrop	9.0	10.6	13.4	3.30	3.37	4.35	12.1	13.0	11.8	2.40	2.08	2.37
Means	**9.7**	**12.3**	**14.7**	**3.22**	**3.94**	**4.46**	**13.3**	**15.9**	**14.5**	**2.48**	**2.43**	**2.40**
SE(±)												
NT[d]		0.67			0.15			1.00			0.100	
CS[e]		0.67			0.16			0.38			0.054	
NT × CS		0.95			0.23			1.22			0.128	
p value												
NT		0.003			0.001			0.21			0.85	
CS		0.072			0.550			0.01			0.05	
NT × CS		0.545			0.359			0.44			0.11	

[a] N0 : No N fertilizer.
[b] Bas : N application of 50 kg N ha^{-1} at planting (basal).
[c] Del : N application of 50 kg N ha^{-1} at 40 days after sowing (delayed).
[d] NT : Timing of N application.
[e] CS : Cropping system.

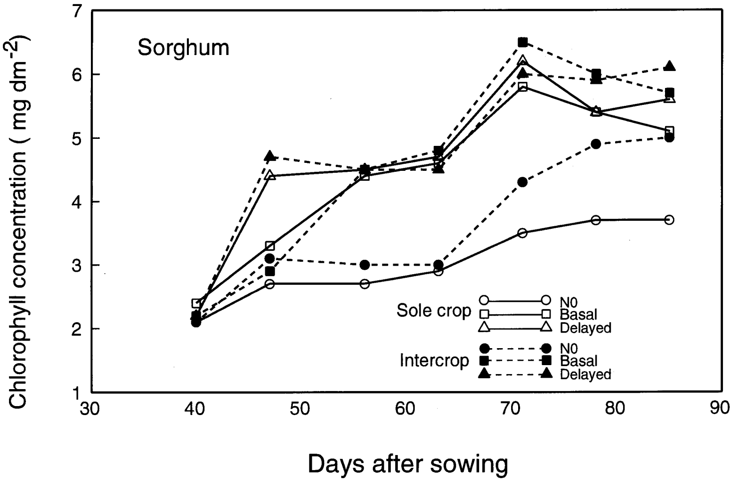

Figure 1. Chlorophyll concentration in selected leaves of sorghum grown as sole crop and as intercrop.

light than intercropped, time of fertilizer application had no effect on LAI of pigeonpea (data not shown).

The chlorophyll content in selected leaves was used as an indicator of N status in plant. Chlorophyll content in sorghum plants (sole crop and intercrop) that received no N fertilizer, was consistently lower than the basal and delayed treatments, but higher, after 65 DAS in sorghum intercropped with pigeonpea than in sole-cropped sorghum (Figure 1).

Table 2. Nitrogen yield (kg ha^{-1}) in grain and in whole plant of sorghum and pigeonpea in sole crop and intercropping systems at harvest. See Table 1 for explanation of N0, Bas, and Del

	Sorghum						Pigeonpea					
	Whole plant			Grain			Whole plant			Grain		
Cropping System	N0	Bas	Del	N0	Bas	Del	N0	Bas	Del	N0	Bas	Del
Sole crop	74.7	96.2	104.2	42.9	53.4	58.8	231	249	240	92.5	99.8	86.0
Intercrop	73.3	87.4	108.6	48.0	54.7	61.2	204	204	203	82.1	76.0	83.7
Means	**74.0**	**91.8**	**106.4**	**45.5**	**54.1**	**60.1**	**218**	**227**	**221**	**87.3**	**87.9**	**84.9**
SE (±)												
NT		4.68			2.83			19.4			5.35	
CS		0.79			2.02			8.6			3.82	
NT × CS		5.47			3.84			24.0			7.24	
p value												
NT		0.004			0.01			0.94			0.91	
CS		0.227			0.42			0.09			0.15	
NT × CS		0.626			0.88			0.94			0.40	

Nitrogen yield

The response of sorghum to added N was evident in both grain N ($p<0.01$) and total N yields ($p<0.004$) when N fertilization was delayed by 40 days (Table 2). Grain N and total N amount in sorghum was similar in sole-cropped and intercropped with pigeonpea. The nitrogen harvest index (NHI, estimated as the ratio of N in grain to the aboveground N in plant) which varied from 0.58 to 0.67 was slightly higher in intercrop than in sole-cropped sorghum, but was not significantly affected by the N treatments. The total N amount in pigeonpea, whether grown as a sole crop or an intercrop with sorghum, did not respond to applied N (Table 2).

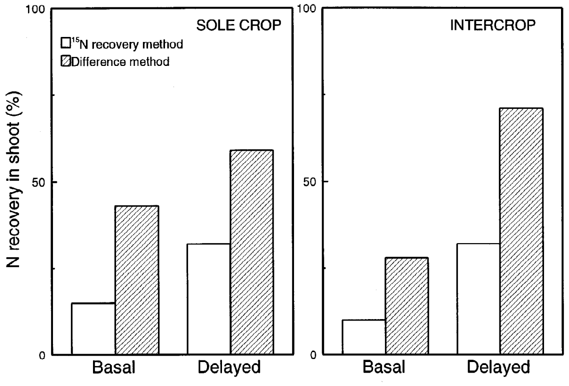

Figure 2. Fertilizer N recovery in shoot of sorghum grown as a sole crop and as an intercrop with pigeonpea at harvest.

Fertilizer nitrogen recovery (FNR)

By including a nonfertilized control N0, we could make comparison between the conventional difference method of determining fertilizer N uptake, and the direct tracer (^{15}N) method (Figure 2). The N recovery by the conventional method was higher than by the tracer method. Delaying N fertilization to sorghum for 40 days significantly ($p<0.001$) increased ^{15}N recovery in shoot from 15 to 32% in sole crop, and from 10–32% in intercrop. Similarly, there was a significant ($p<0.001$) increase in N recovery by the difference method from 43 to 59% in sole crop and from 28 to 71% in intercropped sorghum. Fertilizer N recovery by sole-cropped pigeonpea (14%) was higher than intercropped pigeonpea (2–4%). The low FNR by intercropped pigeonpea is attributed to the fact that no N fertilizer was applied to intercropped pigeonpea.

Proportion of nitrogen derived from fertilizer (N_{dff}), soil (N_{dfs}) and atmosphere (N_{dfa})

Fertilizer N uptake by sorghum and pigeonpea was generally low (0.9–16 kg N ha^{-1}) (Figure 3). Delaying N fertilization to sorghum by 40 days resulted in a doubling of %N_{dff} (Table 3). Soil N accounted for 84–100% of the total N in sorghum, and 26–44% in

Table 3. Fractional contribution of plant N derived from fertilizer (% Ndff), from soil (% Ndfs), and from atmosphere (% Ndfa) of sorghum and pigeonpea in sole crop and intercropping systems at harvest. See Table 1 for explanation of N0, Bas, and Del

	Sorghum									Pigeonpea					
	% Ndff			% Ndfs			% Ndff			% Ndfs			% Ndfa		
Cropping system	N0	Bas	Del	N0	Bas	Del	N0	Bas	Del	N0	Bas	Del	N0	Bas	Del
Sole crop	–	7.7	16.0	100	92.3	84.0	–	2.84	3.24	26.3	44.7	38.7	73.7	52.5	58.1
Intercrop	–	5.8	12.7	100	94.2	87.3	–	0.94	0.44	45.4	36.4	36.2	54.6	62.6	63.4
Means	–	**6.8**	**14.4**	**100**	**93.2**	**85.7**	–	**1.89**	**1.84**	**35.8**	**40.5**	**37.4**	**66.1**	**57.5**	**60.7**
SE (±)															
NT			1.32			1.33			0.352			1.52			1.65
CS			0.27			0.28			0.106			4.96			4.93
NT × CS			1.56			1.56			0.420			5.26			5.29
p value															
NT			<0.001			<0.001			0.008			0.18			0.09
CS			0.049			0.047			0.009			0.73			0.88
NT × CS			0.060			0.090			0.051			0.03			0.003

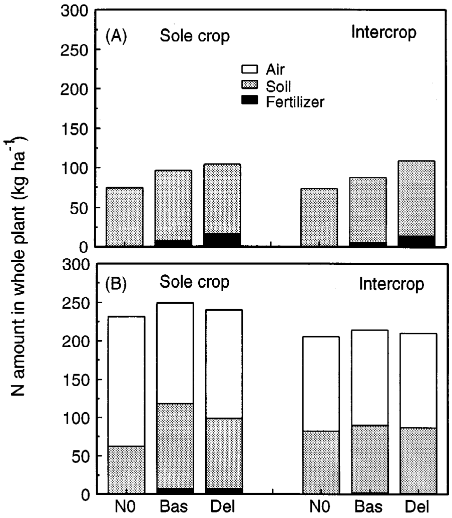

Figure 3. Amount of nitrogen derived from fertilizer, soil and air in sorghum (**A**) and pigeonpea (**B**) in sole and intercrop at harvest. N0: no N fertilizer application, Bas: basal application of 50 kg N ha^{-1} at sowing, and Del: delayed application of 50 kg N ha^{-1} at 40 DAS.

pigeonpea. Contrary to the %N_{dff} data, the %N_{dfs} in sorghum plant was significantly higher when N fertilizer was applied at planting than at 40 DAS. The %N_{dfs} by sorghum intercropped with pigeonpea, was slightly higher (p<0.047) than when grown as a sole crop. Both %N_{dff} and %N_{dfs} were lower with pigeonpea than with sorghum. The high soil N uptake by sorghum and pigeonpea can be attributed to the relatively high mineral N content of the soil.

Biological N_2 fixation by pigeonpea was estimated using the sorghum plants as a reference (Tobita et al., 1994). The proportion and amount of N_{dfa} by pigeonpea, calculated from δ^{15}N values in grain of sorghum ranged +2.3 to +4.1‰, and −0.5 to +1.6‰ in pigeonpea. The % Ndfa values ranged from 57–74%, but were neither affected by timing of N fertilization nor by cropping systems (Figure 3). Despite the relatively initial high mineral N content of the soil, pigeonpea grown as a sole crop fixed 141–169 kg N ha^{-1} of atmospheric N throughout the cropping season, compared to 124 kg N ha^{-1} when grown in association with sorghum.

Nitrate nitrogen in soil

Despite the high nitrate-N ($N0_3$-N) in top soil at planting (3–8 m*M*), it disappeared from the soil solution after 40 days. (Figure 4). Plant N accumulation by sorghum and pigeonpea during 28 DAS was very low (Table 4), indicating that the nitrate which disappeared from the soil solution was not taking by plants, but probably immobilized into the soil organic pool. This phenomenon was also observed at soil depth of 45–60 cm. Fertilizer N applied at 40 DAS was detected in soil solution only in the top soil of control (bare fallow) and sole pigeonpea. For sole-cropped and inter-

Table 4. Nitrogen yield (kg ha^{-1}) in shoot of sorghum and pigeonpea in sole crop and intercropping systems at 28, 40, and 78 days after sowing (DAS). See Table 1 for explanation of N0, Bas, and Del

Cropping system	Sorghum							Pigeonpea						
	DAS 28		DAS 40		DAS 78			DAS 28		DAS 40		DAS 78		
	Bas	Del	Bas	Del	N0	Bas	Del	Bas	Del	Bas	Del	N0	Bas	Del
Sole crop	8.1	5.7	28.4	15.9	56.6	64.3	79.9	2.7	1.4	4.7	4.9	86.5	83.0	77.9
Intercrop	7.6	4 .0	18.6	10.5	32.5	46.6	46.1	2.2	1.7	4.5	4.5	32.0	34.8	35.1
Means	**7.9**	**4.9**	**23.5**	**13.2**	**44.6**	**55.5**	**63.0**	**2.5**	**1.6**	**4.6**	**4.7**	**59.3**	**58.9**	**56.5**
SE±														
NT		1.2		2.75			5.29		0.22		0.55			5.4
p value		0.06		0.02			0.103		0.04		0.47			0.06

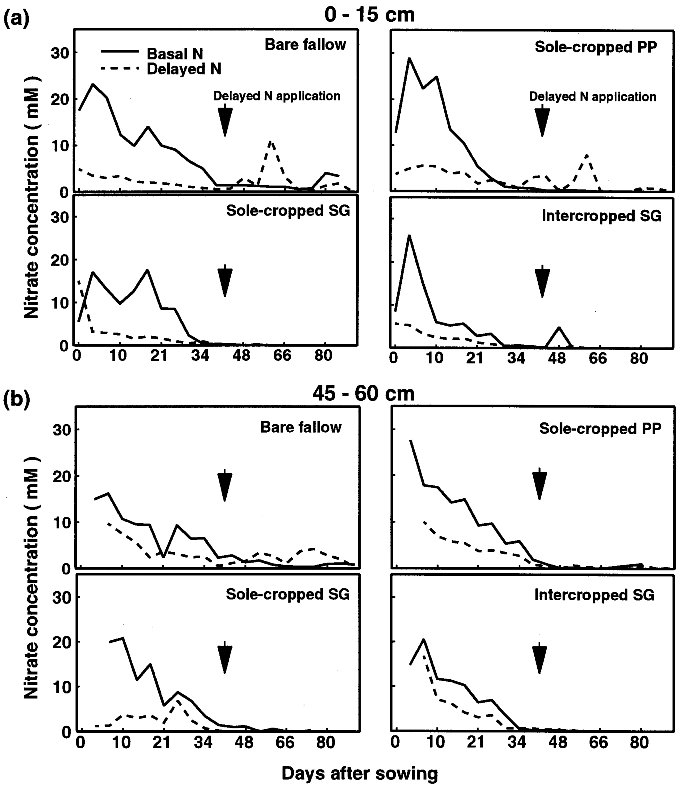

Figure 4. Concentrations of nitrate-N in soil solution measured at (**a**) 0–15 cm and (**b**) 45–60 cm depths with porous cups for sole-cropped sorghum (sole crop SG), sole-cropped pigeonpea (sole-cropped PP), intercropped sorghum (intercropped SG) and a bare fallow (control) treatments. Fertilizer was applied at 50 kg N ha^{-1} at planting (basal), and at 40 DAS (delayed). Arrows denote the time of delayed N fertilization.

cropped sorghum, N0$_3$-N was not detected probably because the urea which was applied at 40 DAS was quickly absorbed by plants. Whereas the N0$_3$-N concentration in soil solution at the later growth stage was very low (not detected), accumulation of N by sorghum plants continued to increase (Table 4). This indicates that plants either absorbed N0$_3$-N efficiently at a low

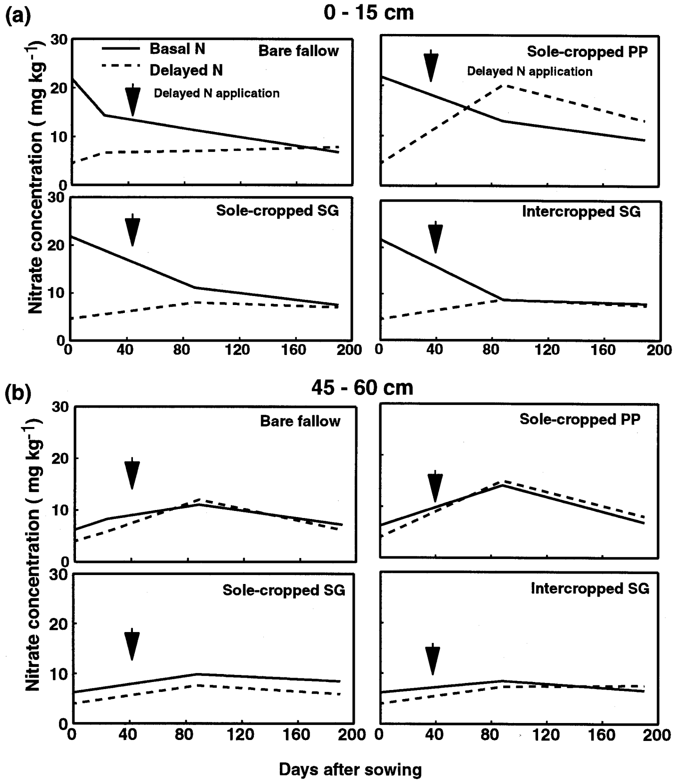

Figure 5. Concentrations of nitrate-N in KCl soil extracts estimated at (**a**) 0–15 cm and (**b**) 45–60 cm depths for sole-cropped sorghum (sole-cropped SG), sole-cropped pigeonpea (sole crop PP), intercropped sorghum (intercropped SG) and a bare fallow (control) treatments. Fertilizer was applied at 50 kg N ha^{-1} at planting (basal), and at 40 DAS (delayed). Arrows denote the time of delayed N fertilization.

concentration or exploited N from the deep soil layers and/or the organic N pool at the latter growth stage.

Nitrate concentration in KCl soil extracts at the beginning of the cropping season, ranged from 4–5 mg kg^{-1} (Figure 5). The effect of basal N application of 50 kg ha^{-1} at planting was detected only at the upper soil layer (0–15 cm) where the nitrate concentration increased to 20 mg kg^{-1}. Contrary to nitrate in soil extracted by suction, the $N0_3$-N concentration in the top soil (except for sole cropped pigeonpea) remained fairly constant after 80 DAS till 180 DAS in KCl extract.

Discussion

Soil solution nitrate dynamics and crop nitrogen uptake

Grain yield of pigeonpea and sorghum without applied N was higher than other reported yields for pigeonpea and sorghum in the semi-arid tropics (Ali, 1990; Gadhia et al., 1993; Tobita et al., 1994) We believe that was because the relatively high mineral N level at the experimental site. The initial soil $N0_3$-N level (5∼10 m*M* Figures 4 & 5) in the no fertilizer treatment is evidence for the inherent high fertility of the soil. Despite this, the delayed application of N did increase GY of sorghum compared with the basal N application (Table 1).

Without application of fertilizer, the nitrate in soil at planting (ca 5 m*M*, 15–20 kg N ha^{-1} at 0–15-cm depth) was sufficient for early crop establishment. Nitrogen fertilization at planting increased mineral N concentration by 3 times in the 0–15 cm depth compared to the soil $N0_3$-N in the delayed plots. The increase in the concentration of mineral $N0_3$-N in plots that received fertilizer N at planting (basal) compared to the N delayed application plots was of the order of 12–15 mg N kg^{-1} of soil.

Assuming a bulk density of 1.5 g cm^{-1} soil in the 0–15 cm depth, the difference in mineral N amount at 0 DAS represents about 27–34 kg N ha^{-1} (60% of applied N). However, this difference in mineral N amount between the basal and delayed N application plots decreased with days after sowing, and gradually disappeared after 40 DAS. The mean plant N accumulation by sole-cropped and intercropped sorghum was higher for basal (7.9 kg N ha^{-1}) than the unfertilized (4.9 kg N ha^{-1}) plot at 28 DAS (Table 4). At 40 DAS (before the delayed N application), sorghum plants which received N fertilizer at planting had accumulated 23.5 kg N ha^{-1} compared to 13 kg N ha^{-1} by the non-fertilized plots (Table 4). However at 78 DAS, the mean N accumulation by plants that received delayed N fertilization was higher compared to plants that received N at planting. Since more than half of the N in soil solution extracted by suction at planting has disappeared at 28 DAS, we believe that most the N was not utilized by plants. Adu-Gyamfi et al. (1996) and De Datta et al. (1990) observed the disappearance of 50–90 kg N ha^{-1} from the top 60-cm soil layer when cumulative rainfall during the first 2–4 weeks after sowing exceeded 300 mm.

It was not clear from our data whether the $N0_3$-N that disappeared during the crop season leached into deep soil layers. If, for example, half of the nitrate that disappeared was lost through leaching every year, the soil would become unproductive after 20 years. We postulate that the nitrate that disappears from the soil solution is incorporated into the soil organic N pool and would become available to the crop later in the growing season. The evidence that supports this is that even though N in soil solution became negligible, plant N accumulation continued to increase. However, further research is needed to advance our knowledge and understanding of the $N0_3$-N that disappears from the soil solution in the early stages of plant growth.

Since more than 80% of the N by sorghum was derived from soil (Figure 3), effective utilization of the initial soil N by sorghum at the early growth stages is important to prevent the disappearance of $N0_3$-N from the crop root zone. In the semi-arid region where the initial monsoon rains in June-July accounts for more than a quarter of the total precipitation during the year, there is a substantial downward water flow, especially in Alfisols, compared to Vertisols. Delaying N fertilization by 40 days to crops would help decrease the amount of fertilizer N that would otherwise disappear from the crop root zone. However, in N limited soils, a starter N application is necessary to stimulate early growth and to enhance grain yield.

Higher concentrations of nitrate in plots cropped with pigeonpea compared with sorghum is due to the uptake of less nitrate from soil by pigeonpea than by sorghum (Figure 4). The mechanisms contributing to this nitrate ‘sparing’ effect have been discussed by Senaratne & Hardarson (1988) and Evans et al. 1996). For pigeonpea, N accumulation increased from 4.6 kg N ha^{-1} at 40 DAS to 82 kg N ha^{-1} for sole crop and 34 kg N ha^{-1} for intercrop at 78 DAS (Table 4). However, at final harvest, there was no difference in the total N accumulation by sole crop and intercrop. (Table 2). This indicates that the N accumulated by intercropped pigeonpea was suppressed by the shading of intercropped sorghum.

Comparison of nitrate in soil profile extracted by suction and KCl methods

There has been a considerable research on methods of extracting soil solution to determining the reliability and accuracy of its composition (Litaor, 1988; Magid & Christiansen, 1993). We compared the concentrations of nitrate in soil profile by suction (ceramic porous cups), and by the KCl extraction methods. Although there was a weak correlation in $N0_3$-N values between the two extraction methods, the $N0_3$-N in soil solution extracted by suction reflected more on the N status in sorghum leaves (using the chlorophyll content as an indicator) than the $N0_3$-N in KCl extract. At 40 DAS, when the nonfertilized sorghum plants showed chlorosis in leaves, the $N0_3$-N in solution extracted by suction was undetectable, although we recorded an appreciable amount of $N0_3$-N in soil extracted by KCl.

It is tempting to conclude from these results which of the two methods of extraction actually reflects the $N0_3$-N concentration in the root zone available for plant uptake. Both methods have their advantages and disadvantages (Litaor, 1988). Hansen & Harris (1975), Shaffer et al. (1979), and Van der Ploeg & Blese (1977) reported that porous cups may not be able to extract all the water from both the micro and macro pores in the soil, therefore $N0_3$-N extracted by suction may not be a true representative of the total $N0_3$-N in soil. On the other hand, sampling the soil and extracting by KCl, is a cheap option, but may not reflect the dynamics of the concentration of $N0_3$-N in the root zone.

Fertilizer nitrogen recovery in plant

Fertilizer N recovery (FNR) calculated for crop uptake with or without the use of labelled ^{15}N has been extensively reviewed (Jansson & Persson, 1985; Jenkinson, et al. 1985; Strong. 1995). However, few studies have compared the FNR of sorghum and pigeonpea in intercropping systems. Where the two FNR methods have been compared, recovery is usually higher for the difference method than for the ^{15}N direct method. This is due to the 'added N interaction' (ANI) of Jenkinson et al. (1985), which is also commented on in detail by Jansson & Persson (1985). The ANI or the priming effect is known to stimulate microbial growth resulting in a higher net mineralization of soil N as compared to N0 treatment. In this study, we also observed significant differences in FNR by the 'difference' and the ^{15}N recovery methods, even though we could not observe any difference in plant N derived from soil between fertilized and non-fertilized plots (Figure 3).

In this study, FNR (difference method) by sole-cropped sorghum in shoot was higher (59%) for the delayed than for the basal treatment (43%). When sorghum was grown in association with pigeonpea, 71% of fertilizer N was recovered by sorghum when fertilization was delayed compared to 28% for basal. Adu-Gyamfi et al. (1996) has reported higher FNR by intercrop sorghum compared to sole crop. Guillard et al. (1995) reported between 0–80% for a range of crops, the FNR decreasing with high N rates.

The plant ^{15}N recovery method showed a similar trend to the difference method, although the values were significantly lower (Figure 2). For an Alfisol of India, Moraghan et al. (1984) reported between 47–64% using ^{15}N, and between 53–88% in above ground parts of sorghum by the difference method. These values are higher than what was recorded in this study, however our values are comparable to those of Tobita et al. (1994) who reported FNR values of 12–20% by sorghum in sole crop and intercrop. Proper timing of N application was reported to increase the FNUE in wheat (Morris & Paulsen, 1985). The difference in FNR values between sole-cropped and intercrop sorghum is explained in terms of different microbial activity of the two systems, and hence the difference in mineralization-immobilization turnover. The difference in FNR by sole-cropped and intercropped pigeonpea is attributed to the ^{15}N fertilizer applied to sole-cropped and not to intercropped pigeonpea (Figure 3).

Biological nitrogen fixation

In estimating BNF using the ^{15}N natural abundance technique, we used sorghum grains (110-day maturity) as the reference crop. This is on the assumption that the validity of a reference plant part might be a less serious problem to the natural abundance method than for the other isotope dilution methods, at least with respect to the variation in soil available N during the growing season (Shearer & Kohl, 1986). Katayama et al. (1995) reported significant (p <0.01) differences in N_{dfa} between sole crop and intercropped pigeonpea. In this study, the amount of N symbiotically fixed by pigeonpea during the entire growth period was 120∼170 kg N ha^{-1}, and there was no significant difference between the cropping systems in spite of the higher value in the sole crop. Tobita et al. (1994) reported similar values for pigeonpea in a pigeonpea/sorghum intercropping. However our values are higher than what was reported earlier on by Katayama et al. (1995). Kumar Rao et al. (1987) reported values of 80–90 kg N ha^{-1} for a medium duration pigeonpea after 160 days.

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