Improvement of Soil and Fertilizer Nitrogen Use Efficiency in Sorghum/Pigeonpea Intercropping

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Abstract

Nitrogen (N) fertilizers play a key role in the burgeoning grain-food production in the semi-arid tropics (SAT). Low commodity prices and relatively high cost of N-fertilization, and increasing concern about the impact of modern agriculture on environmental quality suggest that agriculture should emphasize resource management to either explore more effective and efficient ways to utilize soil- and fertilizer-N, or exploit opportunities for biological N_2-fixation that can augment or substitute for N-fertilizers.

Field experiments were conducted in shallow and medium-deep Alfisols for 3 years to evaluate cereal/legume crop combinations and fertilizer management strategies to improve soil and fertilizer N use efficiency (NFUE), and also to enhance N_2-fixation. The NFUE of sorghum and the dependency of pigeonpea on N_2 from fixation were enhanced by intercropping compared with that in a sole crop. Band-placement of fertilizer-N to sorghum resulted in 36% recovery compared with 19% in split, and 13% in broadcast compared with basal application. Delay of urea-N application until 40 days after sowing (DAS) resulted in a higher grain yield and NFUE in sorghum. Fertilizer-N rate of 50 kg N ha^{-1} applied as band-placement resulted in the highest grain yield and total N accumulation by sorghum and not by pigeonpea. The results suggest that more efficient utilization of N can be achieved by appropriate combination of component crops of intercropping and their management.

Introduction

Semi-arid tropical (SAT) soils are usually low in organic matter (less than 1%) as compared with soils in temperate environments (2-4%). Because organic matter is a source of available-N in the soil, many soils in the SAT are incapable in maintaining N in adequate amounts, and N fertilization is therefore necessary for reasonable high yields on SAT soils.

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Historically, N fertilization of crops in the SAT has been considered as a risky investment because of unpredictable weather in the SAT. Furthermore, soil nitrate can be left unused in the soil in the absence of rainfall, or be lost through leaching by excessive rains at the onset of the planting season (Adu-Gyamfi et al. 1996). These complexities give rise to highly variable yields, as well as variable N-use efficiencies of soil- and applied-N. Yet, fertilizer use in the SAT can be profitable, particularly if combined with improved cultural fertilizer management practices, high yielding varieties (Katyal 1989; Venkateswarlu 1987), and appropriate cropping system combinations.

Vlek (1990) concluded that to achieve self sufficiency in food for the rural population in the African SAT, food production levels have to be increased drastically. Crop production strategies that incorporate a reduced use of fertilizers, while maintaining or increasing yields are desirable. One way to achieve this is to increase resource use efficiency through cropping system combinations.

Problems in current crop production include (a) low commodity prices and relatively high input cost and (b) the increasing concern about the impact of modern agriculture on environmental quality. The effect of nitrate contamination resulting from N leaching has received much attention by environmentalists (Keeney and Follett 1991). In the light of increasing crop production in harmony with nature, agriculture should emphasize resource management and give a greater attention to either exploring more effective and efficient ways to utilize soil- and fertilizer-N or exploit opportunities for biological N_2-fixation (BNF) that can augment or substitute for N-fertilizers.

Cereal/legume intercropping systems offer an economically attractive and ecologically sound means of reducing external input and improving internal resources. The inclusion of legumes in cropping systems, a common practice of resource-poor farmers in the SAT, is a cheap and efficient means of providing N-input to the system. A wide range of crop combinations in pigeonpea-based intercropping systems is found in the SAT of India, and in southern and eastern Africa (Rao and Willey 1980; Venkateswarlu and Subramanian 1990). Yield advantages, efficient light interception, production efficiency, monetary advantage, and improved N_2-fixation of intercropping over sole cropping has been extensively reviewed elsewhere in this book and in other publications (Ali 1990, 1996; Willey 1985, 1996; Ofori and Stern 1987; Kumar Rao et al. 1996). The deep-rooting ability of pigeonpea (Ae et al. 1990) could enhance the possibility of recycling of nutrients, especially N and phosphorus (P) from the deep soil layers, and therefore improve the N-resource use efficiency of the cropping system by capturing and utilizing N in the uppermost soil layer which could otherwise be leached out to deep soil layers (Adu-Gyamfi et al. 1996).

Excellent publications are available on N management and N-use efficiency for sole crops in temperate (Bacon 1995) and mediterranean-type environments (Monteith and Webb 1981), in humid and sub-humid tropical environments (Christianson 1989; Kang and van der Heide 1985), and in the SAT (Katyal, 1989; Christianson and Vlek 1991). On the other hand, few studies have highlighted the intercropping/mixed cropping systems that dominate the agricultural sector in most SAT environments.

The purpose of this paper is to review experimental work done on N-flow in intercropping systems and to examine effective management practices for maximum utilization of soil- and fertilizer-N. Future research needs for intercropping systems are highlighted. We also suggest some guidelines for better utilization of N in the SAT based on recent experimental data on Alfisols and Vertisols at ICRISAT's research locations in India and Africa.

N-fertilizer policies and the food crisis

The SAT stretches over 48 countries in 4 continents and supports more than 700 million people, most of whom live in rural areas. Improved and appropriate fertilizer technologies are expected to play a dominant role in meeting projected long-term food requirements.

Mokwunye and Vlek (1986) reviewed N-fertilizer problems and policies and the constraint to the use of N-fertilizers in the SAT of Africa and concluded that there is a need for appropriate technology and major policy reforms and commitments in at least two areas; (a) to raise fertilizer efficiency, productivity, and response through development of appropriate N fertilizer technology and management and (b) to improve crop response to applied-N through the development of fertilizer-responsive crop varieties and cropping systems and the transfer of this development to farmers.

Crop responsive to applied-N would be most desirable in fertilized, high-input systems. Farmers who practice intercropping in the SAT apply low levels of N; hence the first option is likely to be the most valuable for increasing productivity in low N-fertility SAT environments. Nevertheless, combining crop N-use efficiency and responsive characteristics could be the realistic long-term solution to the problem. Nitrogen fertilizer response is determined by numerous factors, such as crop variety, rainfall, soil quality, fertilizer source and management, cropping pattern, and various agro-climatic factors. In this review, we focus on fertilizer source and management, and cropping system strategies designed to improve N-use efficiency.

Definitions of fertilizer N use efficiency

One agricultural goal is to design cropping systems that use N efficiently. To quantify differences in N-use efficiency between cropping systems, definitions of N-use efficiency and evaluation methods must be developed for analyzing system differences in N-use efficiency. Fertilizer-use efficiency assumes different meanings for different purposes. There is therefore no general agreement as to what constitutes N-efficiency in agriculture. For example, where the purpose is to compare cost effectiveness of applied fertilizers, a simple measure of crop yield per unit fertilizer applied at an economically optimal rate could be the most appropriate measure (e.g., kg grain kg^{-1} N applied). Such a measure ignores the amount of N taken up by the crop.

Moll et al. (1982) defined N-use efficiency as grain production per unit available soil-N. They defined two primary factors of N-use efficiency based on major plant physiological processes as (a) N-uptake efficiency, amount of plant-N at maturity per unit available soil-N and (b) N-utilization efficiency, amount of grain production per unit above-ground plant-N.

To accommodate these factors, Pierce and Rice (1988) substituted available-N with N-supply (the sum of all sources of potentially available N, such as fertilizer-N, residual inorganic-N prior to crop growth, mineralized-N, fixed-N, and depositional-N including atmospheric, irrigation and run-off. Bock (1984) defined N-use efficiency in terms of fertilizer use where yield efficiency is equal to the product of recovery efficiency and physiological efficiency. This definition of N-use efficiency reflects the emphasis of soil fertility research on evaluating crop response to applied-N yields, and is useful within a specific cropping system (Huggins and Pan 1993).

In this paper the nitrogen fertilizer use efficiency (NFUE) is defined as the plant-^{15}N recovered in the aboveground portion per amount of ^{15}N applied.

Determination of N recovery

Apparent recovery method

Traditionally, fertilizer recovery has been calculated as the difference between the fertilized and non-fertilized crop in N-uptake per quantity of applied-N (apparent recovery). The assumption that the quantity of soil-N available to the N-fertilized crop is identical to that available to the unfertilized crop has been found to be invalid (Knopke and Towner 1992; Jenkinson et al. 1985) as fertilized crops frequently take up more soil-N than unfertilized crops. This results in an overestimate of the fertilizer recovery by this method. This phenomenon is referred to as the "priming effect". Strong (1995) suggested that increases in soil-N uptake with fertilization may be due to stimulation of microbial growth by the extra N resulting in increased net mineralization of soil-N. The development of a larger, more effective root system by fertilized plants for the recovery of N could also be a possible explanation.

Plant-^{15}N recovery method

To discriminate between soil-N and fertilizer N, ^{15}N-labeled fertilizers are used. With this method, it is possible to ascertain more accurately the fertilizer-N recovered by a crop (^{15}N recovery). The limitation with this method is that fertilizer-N applied to the soil undergoes exchange with the native soil through mineralization-immobilization turnover. Thus, when the ^{15}N-labeled fertilizer is applied, turnover will cause the inorganic pool to lose ^{15}N by immobilization and to gain non-labeled native soil-N by mineralization (Strong 1995). In our study, we used ^{15}N recovery and apparent recovery methods to compare the N-use efficiencies of component crops in intercropping.

Nitrogen fertilizer use efficiency in the SAT and humid tropics

Sole cropping

The efficiency of plant-N-use depends on several factors, including application time, rate of N applied, method of N-application, and climate-related variables. By carefully managing fertilization, less N may be needed while grain yields and protein may be maintained or increased.

Strong (1995), in his comprehensive review of fertilizer-N recovery of various upland crops in temperate environments, reported plant-^{15}N recovery between 12 and 55% depending on the method, time, and source of application. In most cases, very low fertilizer efficiencies were ascribed to climatic extremes, such as drought, which reduces fertilizer uptake by crops.

For the SAT and humid tropics, studies with cereal crops at different locations in the sub-Saharan Africa confirm that plant uptake of ^{15}N-labeled fertilizer was low (<45% of applied-N), and apparent recovery (AR) of fertilizer-N exceeds measured uptake when using ^{15}N (Mughogho et al. 1986). In an IFDC/ICRISAT Collaborative Research Project on maize and sorghum, Mughogho et al. (1986) observed variations in ^{15}N uptake by plants at different locations in Africa. For example, 45% of ^{15}N recovery was reported for the humid and subhumid tropics compared with 28% for the SAT. Nitrogen losses tended to be quite low (ca. 24%) in the humid tropics, compared with a location in the SAT (Niger, 40%).

Reports by Moraghan et al. (1984 a & b) of ^{15}N experiments with sorghum on Alfisols and Vertisols indicated ^{15}N recovery of above-ground plant parts from 50-64% in 1981 when rainfall was above average and from 54-67% in 1981 when rainfall was near average. On Vertisols, surface and incorporated applications of urea at 80 kg N ha^{-1} resulted in plant-N recovery of 48% during 1980 (Table 1).

Table 1. Methods of fertilizer application on recovery of ^{15}N-labelled urea fertilizer (80 kg N ha^{-1}) by above-ground parts of sorghum growing on Alfisols and Vertisols.

Fertilizer Application		^{15}N recovery			
		1980		1981	
Method	Grain yield (kg ha^{-1})	Vertisol	Alfisol	Vertisol	Alfisol
Split Band	6570	ND	66.9	55.7	63.6
Surface	6140	48.0	55.0	30.5	51.6
Incorporation	6120	48.0	54.1	28.9	50.0
SE (±)	175	1.0	1.1	2.0	2.0
F test	***	***	***	***	***

*** denotes statistical significance at the P=0.001 level
SE indicates the standard error.
Source: Moraghan et al. 1984a & b.

Rotation

Few studies on ^{15}N recovery in intercrops exist in the literature. Patra et al. (1987) reported ^{15}N recovery of 37% for sole crop maize and 49% for a maize-wheat-mung bean rotation. High plant recovery of 49% for maize-beans and 63% for maize-cowpea have been reported (Ssali 1990; Arora et al. 1980). The data suggest that higher N-use efficiency could be achieved by multiple cropping.

Nitrogen fertilizer management studies in sorghum/pigeonpea intercropping at ICRISAT

Realizing the significance of intercropping in the SAT of India and the importance of improving N-use efficiency in the system, we undertook a 5-year study to examine strategies to enhance N_2-fixation and N recovery in a sorghum/pigeonpea intercropping combinations.

The overall goal was to improve crop productivity through a better understanding of N dynamics in cropping systems.

Experimental sites and treatments

The experiments were conducted at ICRISAT Asia Center, Patancheru (17°38'N, 78°21'E), India during the rainy seasons of 1990-1994. The soils were either medium-deep or shallow Alfisols (Ferric Luvisols; Udic Rhodustalf). Sorghum and pigeonpea were grown either sole crops or intercrops. The N-fertilizer management treatments were (a) rate, (b) method, and (c) time of application. The NFUE was estimated using ^{15}N-isotope dilution and the N derived from the atmosphere by the ^{15}N natural abundance method. In all the intercropping treatments, fertilizer-N was applied only to the sorghum row.

Rate and source of application

The amount of fertilizer-N required to obtain maximum yield and high N-recovery depends on the soil type and the inherent N-fertility of the soil. From both economic and environmental perspectives, the rate of N-application is for many farmers the most important fertilizer management decision. In the present study, high N-recovery and grain yield of sorghum were recorded at an application rate of 50 kg N ha^{-1} for both sole and intercrop (Table 2). Nitrogen application beyond 50 kg N ha^{-1} neither increased grain yield nor N-recovery in sorghum. Fertilizer recovery by sole crop pigeonpea was higher than in the intercrop because the sole crop treatment of pigeonpea received an N-application. Thus, in the presence of N-fertilizer, pigeonpea has an ability to utilize fertilizer-N equal to that of sorghum. In the intercropping treatment where fertilizer-N was applied only to the sorghum row (60 cm apart), pigeonpea could recover 3-4% of the fertilizer. This suggests that pigeonpea roots could utilize some of the N applied to the sorghum rows.

Intercropping pigeonpea with sorghum enhanced the dependency of pigeonpea on N_2

Table 2. Rate of fertilizer-N application on grain yield, N-fertilizer use efficiency (NFUE), amount of total-N, and amount of N derived from air (N_{dfa}) of sorghum and pigeonpea in sole crop and intercrop on Alfisols at ICRISAT Asia Center, India in 1991

Cropping system	N level	Grain Yield (kg ha^{-1})		NFUE1) (%)		Total N (kg ha^{-1})		N_{dfa} (kg ha^{-1})
		SG	PP	SG	PP	SG	PP	PP
Sole Crop								
	N_0	600	2080	-	-	28.3	240.8	150.1
	N_{25}	1330	2150	11.2	17.9	35.6	238.8	122.9
	N_{50}	3460	2300	20.9	18.4	57.7	286.5	170.5
	N_{100}	3800	2170	21.5	35.2	73.8	278.5	123.5
Intercrop								
	N_0	490	1690	-	-	20.1	189.3	165.7
	N_{25}	1500	1620	14.7	4.0	36.7	186.2	165.4
	N_{50}	3030	1560	21.0	3.8	57.2	174.0	134.1
	N_{100}	2980	1450	20.5	3.5	62.6	162.9	129.5
Coefficients of variation (%)								
	N	16.7	21.3	24.9	51.8	19.1	18.4	27.9
	CS	16.0	20.3	27.2	59.7	18.3	18.7	24.1
Statistical significance								
	N	***	NS	NS	NS	***	NS	NS
	CS	NS	*	NS	*	NS	***	NS
	N × CS	NS	NS	NS	NS	NS	NS	NS

N_0, N_{25}, N_{50}, N_{100}: Levels of N-fertilizer applied at rate of 0, 25, 50, 100 kg N ha^{-1}.
1)recovery of ^{15}N in grain only
SG: sorghum; PP: pigeonpea
N: nitrogen treatment; CS: cropping system
*$P< 0.05$, **$P<0.01$, ***$P<0.001$ NS: Not significant
Source: Tobita *et al.* (1994)

from fixation, and thus could reduce the cost of N-fertilizer input in cropping systems. A fertilizer rate of 50 kg N ha^{-1} applied to sorghum in a sorghum/pigeonpea intercropping resulted in a higher grain yield and plant-N accumulation. There was no response of pigeonpea to fertilizer-N application.

The N-source used in this study was urea. Even though there is much information on the effect of N-source on cereals and legumes grown as sole crops, few reports, if any, for intercropping exist in the literature. Katyal et al. (1987) recommended that urea and ammonium-containing fertilizers should be better than nitrate fertilizers as an N-source in shallow soils where leaching of mineral-N is intensive. Data from an IFDC/ICRISAT Research Project and a report by Mughogho et al. (1986) showed that both urea and KNO_3 were suitable N-sources for increasing grain yield and ^{15}N recovery in sorghum grown as a sole crop. The effect of sources of N on grain yield and NFUE in cropping systems is an important area where further studies would help increase our knowledge on strategies to enhance NFUE, and, consequently, land productivity, in cropping systems.

Timing

Timing of fertilizer application is another management practice that can affect NFUE compared with basal application. The delay in urea-N application until 40 days after sowing (DAS) resulted in a higher NFUE in sorghum (Table 3). NFUE by sole crop pigeonpea was higher (14.6%) than by intercrop pigeonpea (1.8-3.9%), because fertilizer was applied only to the sorghum rows in the case of the intercrop treatment. Delay of fertilizer application also enhanced the dependence of pigeonpea on atmospheric N_2 (data not shown). Grain yield and total-N of sorghum in the sole crop and intercrop were increased by a delay in N application (Table 3).

In the SAT, some of the soil nitrate unused in the soil during the long dry and wet periods of fallow may be utilized by sorghum at the initial growth stage. In this study, the nitrate concentration in soil solution was monitored using ceramic porous cups, and the delayed N-fertilizer was applied to sorghum at the time the NO_3-N concentration had completely disappeared from the soil solution. The findings of many fertilizer trials consistently show that timing is important for efficient N-use by cereals, as confirmed in this study. Thus, fertilizer-N is more efficiently used when the supply of available-N in the soil is matched with the demand for N by the crop (Myers 1987).

Where N-fertilizers, particularly urea, are applied as top dressing to crops, fertilizer recoveries may be high, which is usual for humid climates. Nevertheless, very low fertilizer recovery may also result from delayed application because of ammonium volatilization of the applied-N or because of dry conditions following application particularly in arid and semi-arid climates (Bacon and Freney 1989). In practice, however, timing of fertilizer application is frequently decided by logistical considerations rather than by agronomic principles.

Table 3. Timing of urea application on grain yield, N-fertilizer use efficiency (NFUE) and total-N amount of sorghum and pigeonpea in sole and intercrop on Alfisol at ICRISAT Asia Center, India, in 1993

Treatment	Grain yield ($t\ ha^{-1}$)		NFUE (%)		Total-N ($t\ ha^{-1}$)	
	SG	PP	SG	PP	SG	PP
Sole crop						
BAS[1]	4.16	2.78	15.0	14.6	96	249
DEL[2]	4.58	2.43	32.2	14.7	104	240
Intercrop						
BAS	3.73	2.08	10.2	3.90	87	204
DEL	4.35	2.37	32.4	1.80	108	202
Standard Error (±)						
N[3]	0.15	0.10	2.54	1.61	4.51	18.0
CS	0.16	0.05	0.31	0.30	0.83	7.9
N × CS	0.21	0.13	2.94	1.89	5.28	22.0
Statistical significance						
N	***	NS	***	**	*	NS
CS	NS	NS	*	**	NS	NS
N × CS	NS	NS	NS	*	NS	NS
Coefficient of variation (%)						
N	7.1	3.8	3.8	9.0	1.6	6.4
N × CS	9.2	10.1	44.1	68.0	12.5	20.6

[1] BAS: Basal application of 50 kg N ha^{-1} at sowing (banding)
[2] DEL: Delayed application of 50 kg N ha^{-1} at 40 DAS (banding)
[3] N : Time of nitrogen application; CS: cropping system
*** $P<0.001$, ** $P<0.01$, *$P<0.05$, NS: Not significant

Method of Fertilization

Three different methods of urea application (broadcast, banding, and split banding) at 25 kg N ha^{-1} were evaluated on medium-deep and shallow Alfisols. On medium-deep Alfisols, banding all the N-fertilizer to the sorghum at planting resulted in higher N recovery (36%) compared with split banding (23%) and broadcasting (19%, Table 4). Our results agree with those of Beyroughty et al. (1986), that surface broadcasting of urea, a popular practice among farmers in the SAT, decreases fertilizer recovery. This loss is aggravated in cereal/legume intercropping situations, where broadcasting fertilizers will unnecessarily provide N to the legume component. Similar results were observed for shallow Alfisols (Table 5). The NFUE was improved by intercropping, suggesting that the sorghum/pigeonpea combination might result in a more efficient utilization of N. The results suggest that for a low fertilizer rate of 25 kg N ha^{-1}, a split application may affect the initial growth of sorghum and later doses would not result in an increased NFUE. Although split-banding application of N-fertilizer has been reported to reduce nitrate leaching and enhance NFUE compared with basal and broadcast applications (De Datta et al. 1990; Abdin and Abrol 1993), Venkateswarlu *et al.* (1981) reported no differences in NFUE between basal and split applications of N (75 kg N ha^{-1}) in an intercropping system.

Cropping systems to enhance ^{15}N recovery

Clear evidence of the beneficial effect of intercropping on fertilizer recovery by sorghum is shown in Table 5. Nitrogen recovery in intercrop sorghum was higher than in sole sorghum, irrespective of the method of fertilizer application. This was reflected in the total plant-N accumulation and grain yield (Table 5). The low N-recovery of pigeonpea in intercropping compared with sole cropping shows that intercropping is highly beneficial in increasing the pigeonpea's dependency on fixed nitrogen. In a pigeonpea-based intercrop, NFUE by sorghum was very much enhanced when it was intercropped with pigeonpea

Table 4. Effect of urea application methods on grain yield, N-fertilizer use efficiency (NFUE), total-N amount, and amount of N derived from air (N_{dfa}) of sorghum and pigeonpea intercrop on a medium-deep Alfisol at ICRISAT Asia Center, India, in 1992

Treatments	Grain Yield		NFUE		Total-N		N_{dfa}
	(t ha^{-1})		(%)		(t ha^{-1})		
	SG	PP	SG	PP	SG	PP	PP
Broadcast	4.01	2.49	19.1	8.0	58.9	139	121
Band	4.24	2.28	36.1	6.3	62.8	130	117
Split	3.56	2.25	22.7	5.2	53.9	124	115
SE(±)1)	0.62	0.13	0.21	0.57	2.96	4.86	7.35
Stat. Sig.2)	NS	NS	***	NS	NS	NS	NS
CV%3)	8.4	9.8	2.3	14.6	9.7	5.4	10.8

1)Standard error
2)Statistical significance
3)Coefficients of variation

Table 5. Grain yield, total N amount, nitrogen use efficiency (NFUE), fractional contribution and amount of N derived from air (N_{dfa}) in pigeonpea-based cropping combinations on Alfisol at ICRISAT Asia Center, in 1993.

Crop combination	Grain yield (t ha^{-1})	Total N (kg N ha^{-1})	NFUE (%)	%N_{dfa} (%)	N_{dfa} (kg N ha^{-1})
Pigeonpea (PP)					
Sole crop	2.2	122.8	19.3	30.4	37.6
Pigeonpea with SG	1.1	89.0	5.7	59.2	52.6
Pigeonpea with PM	2.1	97.4	6.3	73.1	70.6
Pigeonpea with GN	2.3	100.2	6.0	75.4	76.3
Pigeonpea with CP	2.1	113.1	8.5	56.2	65.7
SE (±)1)	*0.7*^{NS}	*18.0*^{NS}	*2.0**	*9.6***	*17.7*^{NS}
CV (%)2)	*35.2*	*17.2*	*22.4*	*16.4*	*29.2*
Sorghum (SG)	6.9	85.3	28.8		
Sorghum with PP	5.4	84.8	35.2		
SE (±)	*1.1*^{NS}	*8.9*^{NS}	*6.6*^{NS}		
CV (%)	*17.5*	*10.4*	*20.5*		
Pearl millet (PM)	4.8	57.6	27.3		
Pearl Millet with PP	3.3	52.9	22.6		
SE (±)	*1.5*^{NS}	*16.5*^{NS}	*13.5*^{NS}		
CV (%)	*37.1*	*29.9*	*54.2*		
Groundnut (GN)	2.3	156.0	26.6	46.3	71.9
Groundnut with PP	0.6	109.1	15.6	69.5	75.4
SE (±)	*0.1***	*4.2***	*2.6**	*13.4*^{NS}	*15.6*^{NS}
CV (%)	*9.0*	*3.2*	*12.4*	*23.1*	*21.2*
Cowpea (CP)	1.5	93.6	21.0	57.3	53.2
Cowpea with PP	0.8	87.3	18.1	69.1	60.2
SE (±)	*0.2*^{NS}	*9.7*^{NS}	*6.6*^{NS}	*7.7*^{NS}	*8.5*^{NS}
CV (%)	22.7	10.7	33.2	12.1	14.9

*, **, and *** denote significant at the P=0.05, P=0.01 and P=0.001, respectively; NS-- not statistically significant.

1)Standard error

2)Coefficient of variation

Katayama et al. 1996. However, no difference in NFUE by pearl millet was observed when it was intercropped with pigeonpea. The results suggest that sorghum/pigeonpea would be a better combination in terms of fertilizer-N recovery than pearl millet/pigeonpea. Intercropping pigeonpea with sorghum and pearl millet increased the dependency of pigeonpea on atmospheric N_2. This could be due to the increased uptake of soil-N by the component crops (Tobita et al. 1994). For example, N derived from fixation in pigeonpea increased from 30% to 59% when intercropped with sorghum, and up to 73% when intercropped with pearl millet.

It is evident from the results of Katayama et al. (1996) that intercropping pigeonpea with legumes, such as groundnut, enhanced pigeonpea's dependency on atmospheric N. Thus, pigeonpea/groundnut intercropping could in the long-term improve the N-resource use in cropping systems in the SAT. Pigeonpea/groundnut intercropping is popular in the SAT, probably because of the high economic returns of groundnut. Among the pigeonpea-based combinations, sorghum/pigeonpea proved to be the most efficient for exploring the soil resources.

Future research agenda

Knowledge on how to improve N-resource use in the SAT by manipulating cropping systems has been discussed. There is, however, a scarcity of research information regarding the use of efficient genotypes of component crops in intercropping under either on-station or on-farm conditions. We suggest the following as priority areas in future research in pigeonpea-based cropping systems:

- Identify sorghum genotypes with high N-recovery and pigeonpea genotypes with high N_2 fixing ability.
- Collect information from farmers' fields with respect to nutrient cycling in pigeonpea-based cropping systems.
- Quantify the amount of fixed-N transferred to the associated sorghum or pearl millet. This information will help understand N-dynamics in cropping systems
- Quantify N-input from atmosphere, soil, and fertilizer at different locations to determine an economic and sustainable balance for maximum use of N-resources available in the SAT.
- Develop simple models to estimate the contribution of soil solution N to the N-supply of cereal crops in intercropping systems, taking into consideration climate and soil data, and fertilizer management practices.

Conclusion

There is detailed information about many factors that affect the efficiency of use of N-fertilizer applied to cereals and legumes. Opportunities to maximize fertilizer use efficiency appear to depend on the ability of the manager to optimize rate, time, and method of N-application. The dilemma of the producer and land manager is to avoid under- or over-fertilization at any period during the cropping cycle. Therefore soil and plant diagnostic tests have a role in providing sound management advice. Over-use of fertilizer in SAT countries with developing economies seems an unlikely prospect because of the relative high cost of fertilizer. There is a high potential to improve NFUE by the proper placement and timing of fertilizer application. Pigeonpea-based intercropping systems might enhance efficient utilization of N in the SAT by increasing the dependency of pigeonpea on biological N-fixation, thereby reducing the cost of N-fertilizer input.

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