Plant and Soil 80, 21–33 (1984). Ms. 5701

Labeled nitrogen fertilizer research with urea in the semi-arid tropics

II. Field studies on a Vertisol

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Received 1 November 1983. Revised January 1984

Key words *Carthamus tinctorius* L. Double-cropping Fertilizer application Nitrogen balance Nitrogen fertilizer Safflower Semi-arid tropics *Sorghum bicolor* L. Urea

Summary Field studies were conducted on an Indian Vertisol to determine the fate of ^{15}N-labeled fertilizers applied to dryland sorghum in two successive rainy seasons. In the 1981 season, a split-band (SB) urea application of 74 kg N/ha, half amounts placed 5 cm deep and 8 cm from opposite sides of plant rows at 4 and 19 days after emergence, was superior to preemergent applications of either surface-applied (S) or incorporated (I) applications at the same rate; 907 mm of rainfall fell during the sorghum growing period. Percentages of applied N recovered in the soil-plant system after the sorghum harvest were 94%, 74%, and 72%, respectively, for the SB, I, and S application methods. Substantial quantities, 39%, 45%, and 42% of the added N for the SB, I, and S treatments, respectively, remained in the soil after the final harvest. Plant utilization of added urea-N was greater in 1980 when rainfall during the growing season was 212 mm less than in 1981. S or I applications of urea at 74 kg N/ha, with above-ground plant ^{15}N recoveries of 48.0% and 48.6%, respectively, were also equally as efficient during 1980. Residual soil N derived from fertilizer was of little value for a sorghum crop in the following rainy season and for a safflower crop in the post-rainy season in a double-cropping system.

Introduction

Extensive areas of Vertisols occur in Africa, Australia, and India[18]. Within India, these soils are located mainly in the central and southern regions; the climate is semi-arid tropical with a short wet season of 2–4.5 months between June and September. Vertisols are potentially very productive when moisture is not a limiting factor; nevertheless, yields of crops grown on these soils in India under traditional farming systems are low[3]. Many Indian Vertisols have traditionally been left fallow during the rainy season and successfully cropped, by use of the stored soil moisture, during the post-rainy season[12]. However, recent research has shown that for areas with relatively dependable rainfall, in excess of 750–800 mm annually, Vertisols can be successfully cropped without irrigation during both the rainy and post-rainy

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seasons[12,27]. In fact, this work has clearly indicated that Vertisols are among the most productive soils in the semi-arid tropics because their high water-holding capacities facilitate growth of crops during drought periods, which are common.

Responses to N fertilizer by dryland cereals growing on Indian Vertisols are reportedly larger in the rainy than in the post-rainy season[10]. Appreciable losses of N fertilizers during the rainy season are suspected[10,23], but detailed N-balance studies with ^{15}N to verify this have not been conducted. Field studies with ^{15}N-labeled fertilizers have been conducted on Vertisols in Australia[8] and the United States[13,14,15]; most of the fertilizer-N was accounted for in the soil-plant system in these studies.

Improved sorghum cultivars under Indian conditions require fertilizer N inputs of up to 150 kg N/ha for optimal production[22]. Indian Vertisols, despite their dark color, have low contents of organic matter and total N[10]; therefore, the amount of N mineralized each year is insufficient for improved cropping systems. Split applications of fertilizer, with banding below the soil surface, are recommended. Although little fertilizer N is used for dryland crops on Vertisols, broadcasting of the fertilizer onto the soil surface would be the most convenient method of application for small dryland farmers in the semi-arid tropics because they lack appropriate equipment for placement of fertilizer. The presence of pedogenic carbonate on the surface of many Vertisols[2] may result in NH_3 volatilization losses from surface-applied, NH_4-containing or NH_3-producing fertilizers. For instance, up to 80% of the N in a surface application of $(NH_4)_2SO_4$ to a Texas Vertisol in a laboratory study was volatilized[9]. Incorporation of N fertilizers normally reduces such losses. Banding certain N fertilizers may increase their efficacy by delaying nitrification[28] or reducing immobilization[24]. Studies of the recovery of fertilizer N by crops therefore necessitated treatments to examine the effect of method of application.

The purpose of this study was to determine (a) the fate of ^{15}N-labeled fertilizers applied to sorghum growing on an Indian Vertisol during the rainy season; (b) the influence of method of placement on N fertilizer efficiency; and (c) the value of any residual fertilizer N for subsequent crop production.

Materials and methods

Soil and experimental sites

The experiments were conducted between 1980 and 1982 on adjacent areas of a Typic Pellusterts at ICRISAT Centre in south-central India. Composite samples of soil from the 0–15 cm depth had the following selected properties: coarse sand = 15%; fine sand = 15%;

silt = 19%; clay = 51%; organic C = 0.60%; inorganic C = 0.52%; pH (soil:H_2O = 1:5) = 8.3; CEC = 56 cmol(Na^+)/kg. The pre-rainy season levels (late May) of soil nitrate-N in the upper 60 cm were 22 and 38 kg/ha, respectively, for the 1980 and 1981 experimental sites. The corresponding values for the upper 120 cm of soil were 37 and 64 kg nitrate-N/ha, respectively. Total N in the 0–15 cm depth averaged 0.053% and 0.047%, respectively, for the 1980 and 1981 sites.

The prior crops for the 1980 site were maize and chickpeas in the rainy and post-rainy season of 1979, respectively; the corresponding uses for the 1981 site were maize and fallow. The experimental sites in both years were relatively flat with a slight grade. The sorghum population was approximately 180,000 plants/ha in both experiments.

Experiment 1

The 1981 experiment consisted of a randomized block design with the following treatments each replicated five times:

(a) check
(b) 18.5 + 18.5 kg urea-N/ha, split banded (SB)
(c) 37 + 37 kg urea-N/ha, SB
(d) 55.5 + 55.5 kg urea-N/ha, SB
(e) 74 + 74 kg urea-N/ha, SB
(f) 74 kg urea-N/ha, surface applied (S)
(g) 74 kg urea-N/ha, incorporated (I).

The SB method of application consisted of placement at 4 and 19 days after emergence of half amounts of the fertilizer treatment at a depth of 5 cm and a distance of 8 cm from the opposite sides of a plant row. The I application method involved fertilizer incorporated to a depth of between 3 and 10 cm. Each plot consisted of seven 45-cm rows of CSH 6 sorghum (*Sorghum bicolor* (L) Moench), 5 m in length. Microplots, enclosed by 30 cm deep steel borders and consisting of seven 45 cm rows, each 2.03 m in length, were located within plots with treatments 'c', 'f', and 'g'. The urea used within microplots was labeled with approximately 5% excess ^{15}N. The urea for treatment 'g' was surface applied and incorporated on June 10, after which sorghum was planted at a depth of 6.5 cm in dry soil (8% moisture). The urea for treatment 'f' was spread uniformly on the soil surface after planting. Sorghum emerged on June 21 after 3.5 cm of rain on June 18. Soil moisture in plots treated with 74 kg urea-N/ha (I) was periodically monitored by gravimetric and neutron thermalization techniques. 'Available' soil water is reported as that in excess of the 1.5 MPa tension value.

Four-meter lengths of rows 3 and 4 were harvested from non-^{15}N-treated plots on September 26. In the case of ^{15}N-treated microplots, central 1.03 m lengths of rows 3, 4, and 5 and 2.03 m lengths of rows 2 and 6 plus the remaining portions of rows 3, 4, and 5 were harvested separately. Agronomic yields were computed from the total harvest, while values for atom % excess ^{15}N were obtained for the plants harvested from the central area. The term 'chaff' is used to describe heads minus grain.

All remaining stover was removed prior to sampling the soil within microplots beween October 19 and October 23. In order to reduce heterogeneity problems during soil sampling of microplots with treatment 'c', twin steel plates separated by a distance of 20 cm were inserted to a depth of 30 cm at right angles to the sorghum rows. Separate soil subsamples from the 0–15 and 15–30 cm depths of all ^{15}N-treated plots were obtained within the enclosed zone from between the interrow centers of rows 1 and 2 and rows 3 and 4; an additional subsampling was done between the interrow centers of rows 3 and 4 and rows 5 and 6. Total N and atom % excess ^{15}N were determined on both subsamples from each depth and averaged. Surplus soil was then returned to the relevant soil depths and repacked to the original bulk density. Soil samples from depth increments between 30 and 170 cm were obtained by combining, mixing, and subsampling six separate cores from within each microplot. All soil samples were air-dried prior to analysis for total N and atom % excess ^{15}N.

Rainfall of 8 mm on October 30 allowed safflower (*Carthamus tinctorius* L.) to be planted between the original sorghum rows. The stand was eventually thinned to give a plant population of about 110,000 plants/ha. The above-ground parts of safflower were harvested, processed, and analyzed in a manner similar to that described for rainy-season sorghum.

Experiment 2

The 1980 experiment consisted of a randomized block design with eleven treatments and five replications. Ten treatments consisted of a factorial combination of five rates of urea (0, 37, 74, 111, and 148 kg N/ha) with the S and I methods of fertilizer application. The two treatments with 74 kg urea-N/ha and the final treatment, 74 kg $NaNO_3$-N/ha applied by application method S, were labeled with approximately 5% excess ^{15}N.

Each plot consisted of thirteen 45 cm rows of CSH 6 sorghum, each 6 m in length. The sorghum was planted on June 23 soon after the arrival of the first monsoon showers. The I and S fertilizer treatments were applied the day before and immediately after planting, respectively.

Two 5 m lengths of interior rows, at least three rows away from plot borders, were harvested after grain physiological maturity was reached. A 5 m length of row 5 was also harvested at the heading stage. Composite soil samples, from selected depths between 0 and 170 cm in all ^{15}N-treated plots, were obtained after the final harvest by combining, mixing, and subsampling soil from five cores. Plant samples were analyzed for total N and, where appropriate, atom % excess ^{15}N; soil samples were analyzed for total N and atom % excess ^{15}N.

Because of lack of rain after the final soil sampling, no post-rainy season crop was planted in October 1980. However, a rainy-season crop of sorghum with a basal dressing of 20 kg urea-N/ha was planted over the entire experimental area in 1981, after completion of the main experiment. Rainfall of 10.6 cm fell during the intervening period. Plants from 5 m lengths of appropriate rows were harvested to measure residual effects from the labeled N fertilizers previously applied.

Chemical analyses

Soil nitrate was determined by a steam distillation method[5]. Plant and soil samples were analyzed for total N and atom % excess ^{15}N by published procedures[6] except for the following modification. Because of problems associated with heat control during the nitrate reduction phase, the recommended reduced iron procedure for inclusion of soil nitrate was replaced by a salicylic acid method[4] involving the addition of water after the nitration phase. As described elsewhere[17], water pretreatment of all soil samples from the various depth increments was needed to ensure quantitative recovery of total N by the Kjeldahl procedure. The need for this water pretreatment was originally reported by Bal[1]. Less than 0.3 μg nitrite-N/g of soil was found in any of the analyzed soil samples.

Percentage recovery or utilization of N fertilizer by plants was calculated by the direct or isotope method[6,16] and by the indirect method based on the difference in N uptake between treated and check plots, expressed as a percentage of the applied N fertilizer. No attempt was made to separate roots from soil material.

Results

Experiment 1

Growing season conditions Pertinent information concerning precipitation, soil moisture, and length of the growing seasons is given in Fig. 1. Total rainfall during the rainy season was 1,070 mm: 907 mm received between planting and harvesting, and an additional 100 mm received before soil sampling within the ^{15}N-treated microplots was finished. Urea granules applied by method S remained visible on the soil surface for 8 days before the occurrence of a rainfall of 3.5 cm.

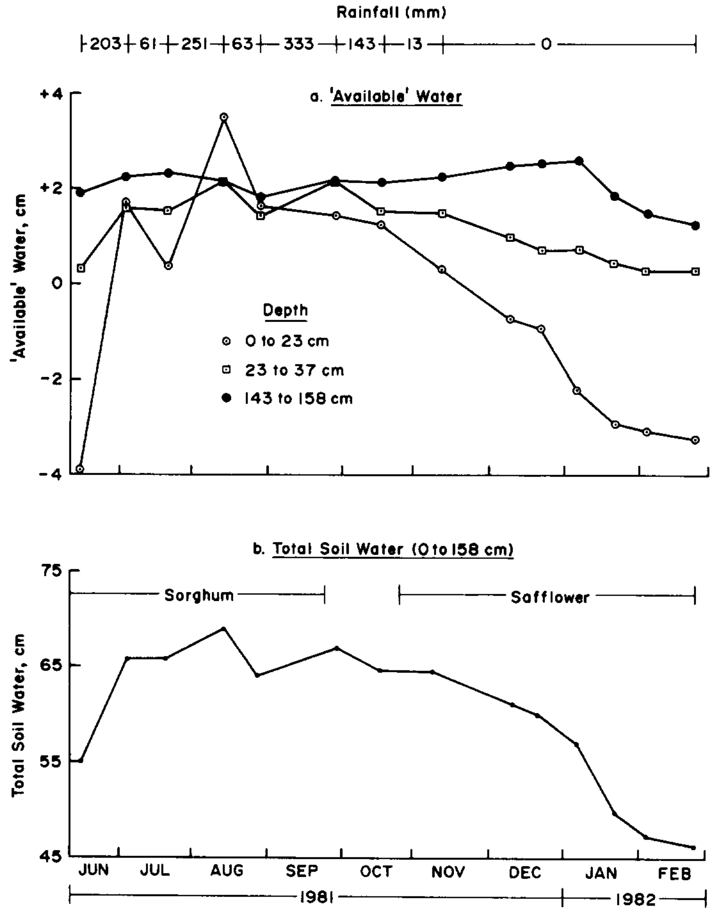

Fig. 1. 'Available' (a) and 'total' (b) soil water during the rainy and post-rainy seasons of 1981–82 in selected soil depth increments of plots treated with 74 kg urea-N/ha (incorporated).

'Available' soil moisture in the upper two depth increments was relatively high throughout the rainy season; the surface-layer data in Fig. 1 are in fact biased on the low side since access to the experimental plots was frequently restricted because of wetness. The 0–23 cm soil depth increment had a moisture content well below that equivalent to the 1.5 MPa tension value before the rainy season started and was again below this value for most of the post-rainy season. The post-rainy season was characterized by successive soil depth increments becoming progressively reduced in 'available' soil water. Safflower growth was entirely dependent on stored soil moisture during this latter season.

Table 1. Influence of rate and method of application of urea-N on yield of dry matter and N in above-ground parts of sorghum grown in the rainy season of 1981

N rate, kg/ha	Application method	Dry matter, kg/ha			Plant N, kg/ha			
		Grain	Stover	Chaff	Grain	Stover	Chaff	Total
0		2,720	3,890	600	25.2	10.4	3.04	38.6
37	Split band	3,610	4,930	730	34.8	14.4	3.72	52.9
74	Split band	5,220	5,830	940	58.7	20.9	4.89	84.4
111	Split band	5,330	5,670	950	57.1	19.6	5.12	81.9
148	Split band	5,310	5,620	930	62.0	21.3	5.29	88.6
74	Surface	4,260	5,300	780	43.4	14.8	3.91	62.1
74	Incorporation	4,110	5,340	790	42.0	14.0	4.14	60.2
$S\bar{x}$		225	112	32	3.1	1.0	0.25	4.1
F value		***	***	***	***	***	***	**

** and *** denote significance at the $P = 0.01$ and $P = 0.001$ levels, respectively. $S\bar{x}$ indicates the standard error of the particular mean value

Table 2. Effect of method of application on the fate of labeled urea-N applied to sorghum at the rate of 74 kg N/ha in the rainy season of 1981

Application method	^{15}N recovery, %				
	Soil	Grain	Stover	Chaff	Total
Split band	38.6	37.7	14.8	3.1	94.2
Surface	41.8	20.9	7.7	1.9	72.3
Incorporation	45.2	20.0	6.9	2.0	74.1
$S\bar{x}$	2.7	1.4	0.7	0.1	2.1
F value	NS	***	***	***	***

NS and *** denote no significance and significance at the $P = 0.001$ level, respectively. $S\bar{x}$ indicates the standard error of the particular mean value

Yield and nitrogen uptake The yield and total N data for above-ground plant parts are given in Table 1. Grain yields were significantly increased by N fertilizer; optimal production was obtained by a banded application, method SB, of 74 kg N/ha. The most striking feature of these data is the marked effect of application method on the efficacy of the three 74 kg urea-N/ha treatments. Application method SB resulted in significantly higher yields of dry matter and greater total N uptake.

Recovery of labeled urea-N was greatest with application method SB (Table 2). The combined soil-plant data show that over 94% of the urea-N applied with this treatment was accounted for in the soil and plant fractions despite the wetness of the growing season. In contrast, with application methods S and I, recoveries were only 72% and 74%, respectively. Incorporation of urea after broadcasting had no beneficial effect under the given experimental conditions.

The greater efficacy of the split-band method of application is

Table 3. Comparison of direct (isotope) and indirect (difference) methods for determining recovery of N-labeled urea fertilizer by above-ground parts of rainy-season sorghum in 1981

Fertilizer application method	N recovery, %	
	Direct	Indirect
Split band	55.7	61.9
Surface	30.5	31.8
Incorporation	28.9	29.1
$S\bar{x}$	2.04	6.0
F value	***	**

** and *** denote significance at $P = 0.01$ and $P = 0.001$ levels, respectively. $S\bar{x}$ indicates the standard error of the particular mean value

Table 4. Recovery of labeled fertilizer N remaining in the soil at the end of the 1981 rainy season as affected by method of application

Application method	^{15}N recovery (%)/depth increment in cm							
	0–15	15–30	30–60	60–90	90–120	120–150	150–170	Total
Split band	21.6	7.8	4.5	2.9	0.9	0.8	0.2	38.6
Surface	21.7	6.4	5.7	2.9	3.0	1.7	0.3	41.8
Incorporation	23.0	8.3	6.4	2.4	3.5	1.3	0.3	45.2
$S\bar{x}$	1.2	0.7	0.8	0.8	0.8	0.2	0.1	2.7
F value	NS	NS	NS	NS	NS	NS	NS	NS

NS denotes no significance. $S\bar{x}$ indicates the standard error of the particular mean value

apparent irrespective of whether N fertilizer recovery was computed by direct or indirect methods (Table 3). However, the use of atom % excess ^{15}N data allowed more precise comparisons of the N fertilizer recovery.

The major part of the ^{15}N-labeled fertilizer in the soil at the end of the rainy season was located in the 0–15 cm depth (Table 4). Method of application had little effect on retention of this N by soil.

Only a small part of the residual labeled N fertilizer applied to rainy-season sorghum was recovered by safflower in the post-rainy season (Table 5). However, there was a trend for dry-matter yields and total N uptake by this crop to be greater from plots receiving urea during the rainy season.

Experiment 2

Growing season conditions Rainfall received during the 1980 rainy season was 733 mm, with 695 mm received during the sorghum growth period. The surface-applied urea granules remained relatively intact on the soil surface for 30 hours before a rainfall of 8 mm; an additional rainfall of 20.8 mm was recorded 4 days later.

Table 5. Influence of rate and method of application of urea-N applied to 1981 rainy-season sorghum on yield and selected characteristics of safflower grown as a 1981–82 post-rainy season crop

N rate, kg/ha	Application method	Dry matter, kg/ha Grain	Stover	Chaff	Total plant N, kg/ha	^{15}N recovery, %
0		780	860	790	23	–
74	Split band	900	1,030	910	27	1.5
74	Surface	1,050	1,270	1,090	32	4.2
74	Incorporation	970	1,250	1,030	30	3.8
$S\bar{x}$		103	112	106	3	1.1
F value		NS	NS	NS	NS	NS

NS denotes no significance. $S\bar{x}$ indicates the standard error of the particular mean value

Yield and nitrogen uptake The data in Table 6 indicate that efficacy of urea was not increased by incorporation of fertilizer within the upper 3–10 cm of soil. In addition, uptake of N from $NaNO_3$ was comparable to that from urea applied at the same rate.

A comparison of direct and indirect methods for determining utilization of fertilizer N from the three labeled sources is given in Table 7. The isotope data revealed that recovery of fertilizer N was maximal by heading time and that a larger proportion of the N from $NaNO_3$ was absorbed. However, the imprecision of the difference method for calculating N recovery prevented any firm conclusion concerning whether use of the nitrate fertilizer source allowed plants to accumulate more total N.

Data showing the residual effects of the 1980 labeled sources on sorghum planted during the 1981 rainy season are given in Table 8. The effects were small, but revoveries were significantly greater for the two urea sources.

Discussion

The seasonal rainfall of 1,070 mm in 1981, in contrast to 733 mm in 1980, was well above the average June–October rainfall of 690 mm for the nearby city of Hyderabad. Utilization of urea, either incorporated after broadcasting or surface applied after planting, by sorghum in the rainy season was less in 1981 than in 1980. The 1981 recovery data indicated that losses of urea by these two application methods exceeded 25%. The data do not allow losses to be subdivided into denitrification and volatilization and leaching fractions. However, the nature of the distribution of residual N with depth, the relatively impermeable nature of the experimental soil, and the observed periodic waterlogging during the growing season suggest that a denitrification

Table 6. Influence of selected N treatments on yield of dry matter and N in above-ground parts of rainy-season sorghum at maturity in 1980

Material	Application method	N rate, kg N/ha	Dry matter, kg/ha			Plant N, kg/ha				Apparent recovery, %
			Grain	Stover	Chaff	Grain	Stover	Chaff	Total	
Check	–	0	3,380	3,230	660	39.5	12.1	3.3	54.9	–
Urea	Incorporation	37	3,900	3,580	720	48.6	14.8	4.9	68.3	36.3
Urea	Incorporation	74	4,420	4,140	800	62.3	20.6	4.7	87.6	44.2
Urea	Incorporation	111	4,910	4,600	880	70.4	25.1	6.5	101.9	42.4
Urea	Incorporation	148	4,880	4,500	840	74.3	27.6	6.5	108.4	36.2
Urea	Surface	37	4,480	3,990	850	58.6	17.2	6.2	82.1	73.6
Urea	Surface	74	4,470	4,250	800	62.7	19.8	4.6	87.1	43.5
Urea	Surface	111	4,760	4,240	850	68.0	21.9	6.5	96.3	37.3
Urea	Surface	148	4,860	4,400	840	72.4	27.7	6.3	106.4	34.8
$NaNO_3$	Surface	74	4,480	4,330	830	64.8	21.1	5.0	90.8	48.6
$S\bar{x}$			185	182	35	2.6	1.3	0.3	3.6	5.0
F value			***	***	***	***	***	***	***	**

** and *** denote significance at $P = 0.01$ and $P = 0.001$ levels, respectively. $S\bar{x}$ indicates the standard error of the particular mean value

Table 7. Comparison of direct (isotope) and indirect (difference) methods at two harvest dates for determining N recovery from two different labeled N sources (74 kg N/ha) by above-ground parts of sorghum during the 1980 rainy season

Material	Application method	N recovery, %			
		Heading		Maturity	
		Direct	Indirect	Direct	Indirect
Urea	Surface	53.2	43.7	48.0	43.5
	Incorporation	49.1	38.6	48.6	44.2
$NaNO_3$	Surface	60.9	58.1	57.1	48.6
$S\bar{x}$		4.0	7.5	1.0	4.2
F value		NS	NS	***	NS

NS and *** denote no significance and significance at $P = 0.001$ level, respectively. $S\bar{x}$ indicates the standard error of the particular mean value

mechanism was at least partly involved. The unaccounted-for N fertilizer exceeded that reported for Vertisols under different climatic conditions in Australia[8] and the United States[14,15,26].

Although Vertisols once wet are only slowly permeable to water, N from ^{15}N-labeled fertilizers was found in drainage waters from such soils in Texas[13,14]. It was concluded that large connected soil pores allowed nitrate-containing leachates to bypass other soil water inside soil structural units. Results of an Australian study[7] suggest that the likelihood of denitrification in Vertisols is a function of the interaction of rate of flow of nitrate through anaerobic zones and of oxygen through water films and unfilled pores. The oxygen content would be affected by availability of a carbon source. Soil organic matter in most Indian Vertisols is low[10], and less is known about its availability for a heterotrophic microbial population.

The N recovery and the agronomic efficacy were unexpectedly similar for surface applied and incorporated urea. This may have been due to low soil moisture that restricted urease activity and consequent buildup of ammonia and its volatilization at the surface of the soil. Such an explanation was also advanced to explain the lack of ammonia volatilization from surface-applied urea in northern Australia[19]. However, light rain showers, insufficient to leach urea into the soil, could have resulted in appreciable losses of urea surface applied to relatively dry Vertisols. The likelihood of ammonia volatilization losses in rainfed agriculture in the semi-arid tropics needs further study.

Of particular interest was the finding that banding urea in two split applications in the very wet 1981 season, when waterlogging occurred several times, reduced the amount of unaccounted-for N to less than 6%. The effects of banding and time of application were confounded; additional studies are needed to determine their relative importance.

Table 8. Effect of labeled N fertilizer applied in 1980 on sorghum grown in the 1981 rainy season

Source	Application method	Rate, kg N/ha	Dry matter, kg/ha			Plant N, kg/ha	^{15}N recovery, %
			Grain	Stover	Chaff		
1980 Treatment							
Check	–	–	2,870	3,350	650	38.5	
Urea	Incorporation	74	2,320	2,610	560	31.3	1.6
Urea	Surface	74	2,540	3,010	610	33.1	1.7
$NaNO_3$	Surface	74	2,700	3,130	610	34.2	1.3
$S\bar{x}$			176	181	30	2.0	0.1
F value			NS	NS	NS	NS	*

NS and * denote no significance and significance at $P = 0.05$ level, respectively. $S\bar{x}$ indicates the standard error of the particular mean value

The soil ^{15}N recoveries, particularly from the 0–15 cm depth, indicate that immobilization of N was not greatly affected by banding. Split applications of N fertilizer, apart from any agronomic advantage, give farmers some additional control over input costs. The second application may be eliminated when yields are likely to be low because of drought conditions, pest attack, or poor stands.

Turnover of inorganic N between inorganic and active organic phases can affect interpretation of recovery data based on isotope comparisons[11]. However, the agreement between the direct and indirect methods for determining fertilizer utilization was generally good in our study.

The residual fertilizer N in the soil was of limited availability for subsequent crops during the post-rainy and rainy seasons. This finding is in agreement with results from irrigated studies[21,25] on an alluvial soil of the Indo-Gangetic Plain. Apart from the availability per se of the residual fertilizer N, limited soil moisture in the surface layer would also restrict its availability during a post-rainy season. The retention of significant quantities of fertilizer N in this Indian Vertisol low in total N raises the unanswered question of the consequences of long-term N fertilization associated with introduction of improved cropping systems. Additional studies not reported here suggest that little of the residual-N in the soil was present as fixed ammonium. Also, the levels of 2*M* KCl-extractable ammonium-N + nitrate-N in the surface layer did not account for the residual fertilizer N. The residual N is thus believed to be mainly organic N, a portion of which was probably associated with sorghum roots. Sorghum roots in one study[20] reportedly contained 12–22 kg N/ha.

An important feature of these results is the demonstration that good uptake of fertilizer N is possible in the dryland Vertisol areas of India. Previously there were no ^{15}N data available to indicate the efficiency of fertilizer N use on a Vertisol in the semi-arid tropics of India.

Acknowledgements The authors express sincere thanks to Mrs. Seetha and Mr. Pradhasaradhi for competent laboratory assistance, to Mr. P. R. Murthy, Syed Ali, and Mohan Rao for their dedicated work on this project and to Miss Teresa Papachek for secretarial help. Gratitude is due to North Dakota State University for providing leave to the senior author to participate in this study.

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