The effect of plant residues on plant uptake and leaching of soil and fertilizer nitrogen in a tropical red earth soil

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Abstract. Two field experiments, in which differing amounts and types of plant residues were incorporated into a red earth soil, were conducted at Katherine, N.T., Australia. The aim of the work was to evaluate the effect of the residues on uptake of soil and fertilizer N by a subsequent sorghum crop, on the accumulation and leaching of nitrate, and on losses of N.

Stubble of grain sorghum applied at an exceptionally high rate (~ 18 000 kg ha^{-1}) reduced uptake of N by sorghum by 13% and depressed the accumulation of nitrate under a crop and particularly under a fallow.

Loss of fertilizer N, movement of nitrate down the profile, and uptake by the crop was studied in another experiment after application of N as $^{15}NH_4$ $^{15}NO_3$ to field micro-plots. By four weeks after fertilizer application 14% had been lost from the soil-plant system and by crop maturity 36 per cent had been lost. The pattern of ^{15}N distribution in the profile suggested that losses below 150 cm had occurred during crop growth. The recovery of ^{15}N by the crop alone ranged from 16 to 32 per cent. There was an apparent loss of N from the crop between anthesis and maturity. Residue levels common to sorghum crops in the region (~ 2000 kg ha^{-1}) did not significantly affect uptake by a subsequent sorghum crop, N losses, or distribution of nitrate in the profile.

The high intensity summer rains of the Katherine-Darwin region of northern Australia provide conditions conducive to leaching of nitrate beyond the root zone of sorghum crops growing in red earth soils [28, 7]. However, decomposing plant residues may reduce these losses by immobilizing some of the nitrate for a time. Thus, it was suggested [26] that rapid decomposition of plant residues under tropical conditions might give an initial immobilization of N followed by remineralization later in the same growing season. If this is so, N that would otherwise have been leached from the plant root zone would be retained and become available later when the crop's requirement was greater.

Reports that substantial immobilization of N by decomposing cereal stubble has a detrimental effect on plant growth are mainly from laboratory experiments [4, 24]. In the field the effects of decomposing plant material on the uptake of N by crops are by no means clear. There are reports that decomposing legume stubble released N and stimulated plant uptake [29]. Ferguson [8] reported the results of long-term trials in which the return of large amounts of stubble over seven years had no effect on wheat yields under

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Table 1. Some soil characters from the site of experiment 2 and the soil nitrate profiles at the beginning of each experiment (Experiment 2 samples for nitrate-N at planting, Experiment 1 sampled 13th September)

Depth	Soil NO_3-N, $\mu g\ g^{-1}$		Total N	pH	Water retentivity (% grav) at:	
(cm)	Exp. 1	Exp. 2	%		– 0.03 MPa	– 1.5 MPa
0–20	5.3	4.4	0.076	6.6	18.7	11.9
20–40	1.9	7.0	0.046	6.5	21.9	15.3
40–60	1.8	6.1	0.032	6.6	23.6	16.8
60–80	2.1	1.6	0.027	6.7	23.9	17.2
80–100	1.5	0.6	0.026	6.7	23.8	17.3
100–120	2.1	0.6	0.025	6.7	22.1	17.6
120–150	1.9	0.6	0.024	6.5	22.2	18.0

Canadian climatic conditions. These findings were later supported by ^{15}N-microplot studies [13]. Craswell [5, 6] on the other hand found that both wheat and sorghum stubble caused extra immobilization of added N in experiments with fallow soil in south-east Queensland. Losses were reduced with wheat straw but not with sorghum stubble.

The results of two experiments on the effects of plant residues on uptake of N by plants and leaching of nitrate in the soil, under tropical conditions, are reported in this paper. The aim of the first was to study the effects of incorporating sorghum stover on available soil N and uptake by grain sorghum. The second experiment was designed to determine the extent of losses of N from the soil-plant system in the presence or absence of plant residues, using ^{15}N-labelled fertilizers.

Methods

The experiments were conducted at Katherine Research Station, Northern Territory. At Katherine (latitude 14.3°S, longitude 132.3°E and altitude 108 m) the mean annual rainfall is 900 mm, 83% of which falls in summer between December and March [21]. All experiments were on Tindall clay loam soil [1] (formerly included in the Tippera series [23]). This is a well-drained red earth (Northcote [20] key Gn 3.11) or oxic paleustalf [22] which is towards the heavier-textured end of the spectrum of red earth soils that occur widely in the Katherine-Darwin area. It is a clay loam at the surface, grading before 45 cm to a clay. Some soil characteristics from the experimental sites are given in table 1.

Experiment 1: The accumulation of nitrate-N in fallow soil and the uptake of N by sorghum in plots with and without sorghum stubble incorporated in the surface soil were measured in experiment 1. Four large unreplicated plots (20 m x 22 m) were set up in August 1971 on an area that carried ungrazed grain sorghum stubble from the previous season. The treatments were established by cutting the stubble at ground level on half the area and spreading it evenly over the other half, so that the total above ground stubble on the stubble-treated area was 17 600 kg ha^{-1} at a N concentration of 0.55%.

These two areas were then split so that half of each could be planted to grain sorghum while the other half remained bare fallow. All plots were rotary-hoed in November and chisel-ploughed in early December 1971. A basal application of 48 kg P ha^{-1} as triple superphosphate was drilled-in in early December and the two grain sorghum plots planted in 45 cm rows with Pioneer 846 at 8 kg ha^{-1} on December 20 following rotary hoeing and double harrowing. The crop emerged on December 27.

Plant dry matter yield and nitrogen content were determined on the sorghum crop on four occasions – 25 days (floral initiation), 46 days (mid-elongation), 80 days (anthesis) and 114 days (physiological maturity) after emergence. Four quadrats of 0.5 m^2 were cut at ground level, dried at 80°C for dry matter determination, ground and analyzed for total N. Soil samples were taken for soil moisture, ammonium and nitrate-N analysis on September 6 1971, at sowing, and at each of the plant samplings. Four cores were collected per plot in a transect across the row and were sectioned into 0–10, 10–20, 20–40, 40–60, 60–80, 80–100, 100–120 and 120–150 cm layers. Nitrate was extracted immediately from soil samples with water, and ammonium with 2 M KCl using 1:5 soil: extractant ratio. Nitrate-N was determined on all samples using the nitrate electrode [12], and ammonium-N was determined on 0–20 cm samples by steam distillation [3].

Experiment 2: This experiment, in which the fertilizer was labelled with ^{15}N, allowed fertilizer N losses to be estimated, and plant uptake of N from fertilizer to be studied at more realistic rates of plant residue application.

There were five treatments:

Treatment	Stubble or Residue Added	Stubble % N	Fertilizer
1	^{15}N labelled (sorghum)	1.19%	NH_4NO_3
2	Unlabelled (Townsville stylo (*Stylosanthes humilis*))	1.84%	$^{15}NH_4$ $^{15}NO_3$
3	Unlabelled (sorghum)	0.29%	$^{15}NH_4$ $^{15}NO_3$
4	No stubble	–	$^{15}NH_4$ $^{15}NO_3$
5	No stubble	–	no fertilizer

The ^{15}N labelled sorghum was material grown in solution culture and harvested prior to panicle emergence. It was thus higher in N than the unlabelled sorghum stem and leaf material obtained from field-grown mature plants. The residue of the legume, Townsville stylo, was from field-grown mature plants. The stubble and residues were applied at 2000 kg ha^{-1} and the ^{15}N fertilizer was 7.63 atom percent enrichment. Treatment 5 was included when it was realized that there was insufficient ^{15}N-stubble for 9 microplots in treatment 1. The treatments were randomized within three replicate blocks in an area that had been cropped to grain sorghum in the previous year. The microplots containing the ^{15}N-labelled material were within rectangular open-ended steel frames 30 cm deep, which were pressed into the moist soil

Table 2. Above ground dry matter and nitrogen yields of grain sorghum at different stages of growth in the presence or absence of incorporated stubble (Experiment 1)

Stage of growth	No stubble		Plus stubble	
	DM Yield kg ha^{-1}	N Yield kg ha^{-1}	DM Yield kg ha^{-1}	N Yield kg ha^{-1}
Floral initiation	149	4.0	168	4.1
Mid-elongation	711	13.5	604	11.1
Anthesis	3500	24.1	4010	23.7
Physiological maturity	5225	33.8	4623	29.3
Grain yield	1890	20.2	1645	16.4

profile with minimal soil distrubance, so that 2 cm remained above the soil surface to prevent run-on and run-off. They were rectangular (45 cm × 55.5 cm) so that a single row of sorghum planted centrally along the long axis had similar crop geometry to that of the bordering bulk crop planted in 45 cm rows. They were installed in rows of six, with 8 rows of bulk crop between each row of microplots. Along the row, 2 metres separated the microplots and this area was planted by hand.

To reduce variation between soil in the microplots, the top 10 cm of each replicate of 12 microplots was removed, mixed thoroughly and the mixed soil free of the previous year's stover returned.

Both the experimental area and surrounding area received 25 kg P ha^{-1} as triple superphosphate broadcast prior to the installation of the microplots. The surrounding area received 50 kg N ha^{-1} as ammonium nitrate banded below the seed, and was planted with the grain sorghum hybrid Pioneer 846 in 45 cm rows at 8 kg ha^{-1}.

Within the microplots, the fertilizer was banded below and 5 cm to the side of the seed on January 9 and 10 1973. The plant residues used in treatments 1–3, were cut into 5 cm lengths and mixed with the top 0–10 cm soil. The seed was placed at 5 cm depth in a single row in each microplot on January 11. The whole area was spray irrigated with 23 mm on January 12 and the crop emerged on January 16.

Treatment 5 was sampled only at crop maturity. The other treatments were sampled at three stages of crop growth – floral initiation, anthesis and physiological maturity. Two replicates of treatment 1 were sampled; three replicates of the other treatments. The plant material was cut at ground level, subdivided into stems, leaves and panicles, and dried at 80°C. The grain was separated and the remainder of the panicles was retained and referred to as chaff.

For recovery of ^{15}N in soil, the 0–10 cm and 10–20 cm layers were removed, mixed and subsampled, while the remaining layers (20–40, 40–60, 60–80, 80–100, 100–120 and 120–150 cm) were sampled by taking 5 cores with a 50 mm auger. Soil moisture was determined immediately on a small subsample from each depth, and the remainder was air-dried in thin layers on trays, and subsequently stored in large plastic bags. Roots were separated

Table 3. Rainfall (mm) received at experimental sites

Month	Experiment		Long-term average (Slatyer 1960)
	1 1970/71	2 1972/73	
August	5		0
September	30		4
October	11		29
November	83	21	77
December	223	38	198
January	43	318[1]	232
February	292	201	180
March	220	216	150
April	46	15	20
May	0	0	7
Total	953	809	897

[1] Plus 23 mm irrigation. January rainfall plus irrigation received after fertilizer addition was 219 mm

from 2 kg subsamples of the 0–10 and 10–20 cm layers, by hand picking. Since only 0.5 to 0.6% of the applied ^{15}N was recovered therein, no further root separations were made.

All plant parts and soil samples were analyzed for total N and ^{15}N enrichment. Total N was by Kjeldahl digestion – the potassium permanganate and reduced iron modification being used to recover nitrate and nitrite in the soils, and the salicyclic acid modification being used for plant material. The digests were distilled in a stainless steel apparatus and the ammonia titrated with sulphuric acid. ^{15}N enrichment was determined with a Micromass 602E mass spectrometer.

Results

Experiment 1: The content of N in sorghum at maturity was reduced by 13% when stubble was incorporated into the soil (Table 2). This resulted in lower grain yield and grain N content. The pattern of rainfall in the 1971–72 growing season (Table 3) was undoubtedly a major factor in these results. With 223 mm in December, decomposition of the applied residues would have commenced. However, a prolonged hot, dry period through January and the first half of February would have halted decomposition and immobilization of the soil mineral N. Thus there were no differences in production and N uptake at floral initiation (25 days), mid-elongation (46 days) and anthesis (80 days).

Leaching of nitrate-N to depths below the active root zone in the soil occurred in fallow and cropped soil in the presence and absence of incorporated stubble (Figure 1e). Annual crops at Katherine effectively exploit only the nitrate in the top 60 cm [27] and a large proportion of the soil nitrate under fallow had leached beyond this depth. The effect of the incorporated

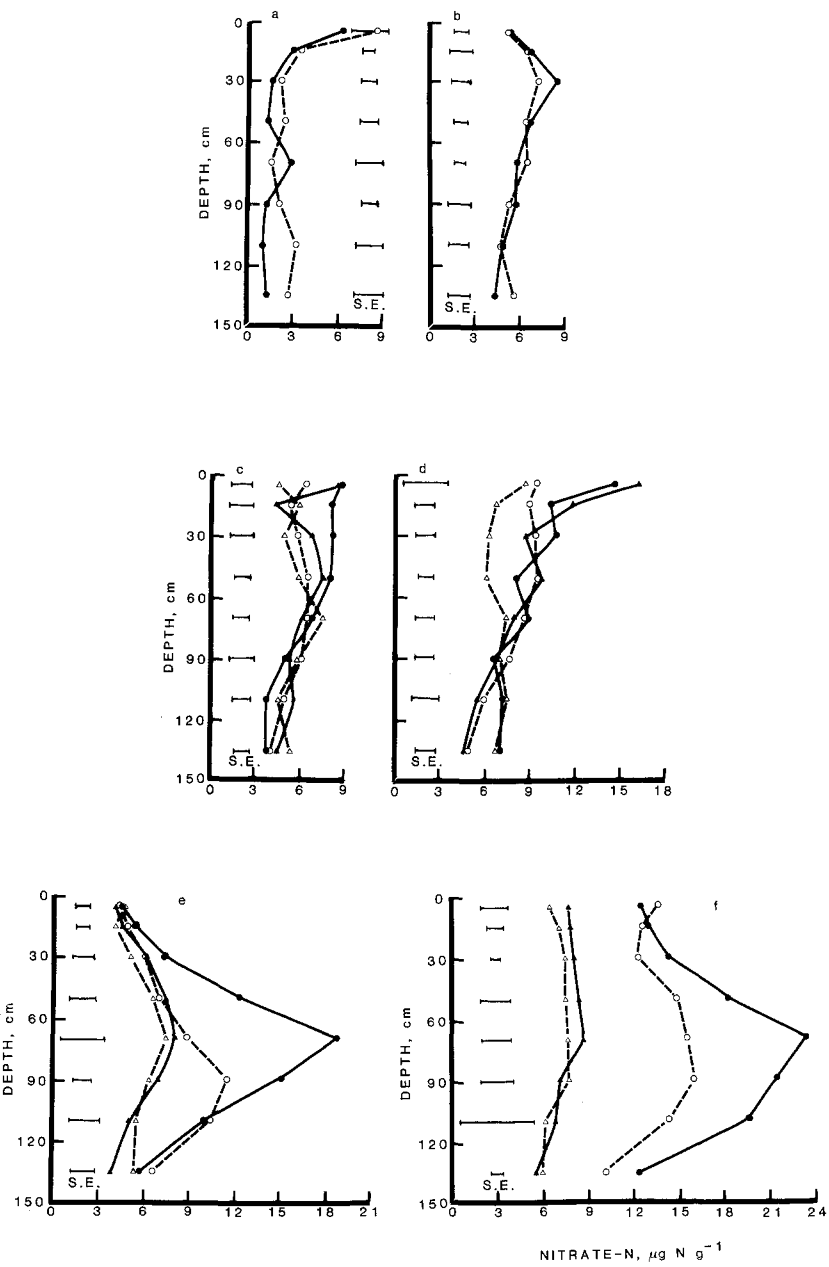

Figure 1. Soil nitrate-N profiles at various times with respect to sowing of grain sorghum showing the effect of incorporation of grain sorghum straw. (—•—) no stubble, fallow; --o-- stubble, fallow; —▲— no stubble, cropped; --Δ-- stubble cropped). (a) 105 days before sowing, (b) 5 days before sowing, (c) 25 days after sowing, (d) 46 days after sowing, (e) 80 days after sowing, and (f) 114 days after sowing. Stubble treatments were applied four months before sowing.

stubble on soil nitrate-N increased throughout the 219 day observation period (Figure 1a–e). There were no differences when observations commenced, but five days before planting there was less nitrate-N in the 20–40 cm layer in the stubble treatments. This stubble effect increased in magnitude until at 114 days after the sowing date there was substantially less nitrate leached below 60 cm in the stubble treatment. It appeared that the stubble, while not affecting the leaching process, reduced leaching losses through reducing the quantities of nitrate available for leaching. In the presence of the growing sorghum crop, the major influence of stubble on soil nitrate appeared to be at 46 days after sowing (Figure 1d), when there appeared to be substantially less nitrate-N in the top 60 cm with stubble. In general, soil nitrate-N levels in the rooting zone were of a level where no limitation to crop growth would be expected, particularly as yield levels and crop requirement for N were below average.

Experiment 2: The relatively poor grain yields (Table 4) are believed to be due mainly to water deficits during grain filling. Rainfall was slightly below average with a slightly early finish to the growing season (Table 3).

Plant residues of either the legume Townsville stylo, or of sorghum added to the microplots had no statistically significant effect on the uptake of ^{15}N by the crop, and no effect on the loss of ^{15}N from the soil-plant system. Results presented in Tables 4 and 5 are therefore the means of treatments 2, 3 and 4. Uptake of ^{15}N from fertilizer was relatively small – 34.7% of the N applied was taken up before anthesis but only 23.7% uptake was measured at crop maturity (Table 4). The apparent loss of N from the plant between anthesis and maturity occurred despite an increase in plant dry matter production. Of the ^{15}N applied in sorghum stubble, only small quantities were recovered by the subsequent sorghum crops – 8.7% at anthesis, and 5.2% at maturity (Table 4). The total of applied fertilizer ^{15}N in the whole soil-plant system was 64%, somewhat less than is often achieved in this type of experiment (Table 5).

Of the 40–53% of the ^{15}N remaining in the soil at the different harvests (Table 5), that in the subsoil was in the nitrate form, whereas that retained in the surface layers had been immobilized, and presumably was present in microbial cells and organic matter (data not shown).

The ^{15}N in the soil moved down the profile rapidly as the wet season progressed (Figure 2). The main zone of accumulation reached 60–100 cm depth by floral initiation, 80–120 cm by anthesis and 100–150 cm by maturity. Little, if any, ^{15}N appeared to have been leached beyond 150 cm by anthesis (Figure 2b), but by maturity some leaching losses may have occurred (Figure 2c).

Discussion

Low recovery of fertilizer N by grain sorghum on this red earth soil has been recorded previously [14, 15, 16] and was confirmed by the results of this

Table 4. Dry matter production, N content and recovery of ^{15}N in different sorghum plant parts, from N applied in stubble or as fertilizer to 0.25 m^2 microplots of Tindall clay loam (Experiment 2)

Stage of growth and plant part	^{15}N stubble Unlab. fertilizer			Unlab. stubble[1] ^{15}N fertilizer			No stubble No fertilizer	
	DM $g\ m^{-2}$	N $g\ m^{-2}$	recovery %	DM $g\ m^{-2}$	N $g\ m^{-2}$	recovery %	DM $g\ m^{-2}$	N $g\ m^{-2}$
Initiation								
– whole plant	78 (12)[2]	1.27 (0.36)	2.3 (3.8)	100 (9)	2.23 (0.21)	26.0 (2.9)		
Anthesis								
– straw	480 (36)	4.35 (0.56)	8.2 (2.5)	450 (30)	5.33 (0.47)	32.4 (2.1)		
– panicle	45 (7)	0.61 (0.13)	0.6 (0.9)	42 (6)	0.61 (0.11)	3.3 (0.7)		
– total	524 (40)	4.97 (0.65)	8.7 (2.9)	493 (33)	5.94 (0.54)	34.7 (2.5)		
Maturity								
– straw	466 (62)	2.10 (0.61)	1.2 (3.0)	435 (48)	2.06 (0.48)	11.2 (2.3)	208 (62)	1.26 (0.61)
– chaff	102 (18)	0.96 (0.18)	1.0 (1.3)	78 (14)	0.65 (0.14)	3.6 (1.0)	66 (18)	0.63 (0.18)
– grain	159 (51)	2.38 (0.64)	3.0 (3.9)	128 (39)	1.75 (0.49)	8.9 (3.0)	110 (51)	1.81 (0.64)
– total	727 (114)	5.43 (1.14)	5.2 (4.4)	64 (88)	4.47 (0.88)	23.7 (3.4)	383 (114)	3.69 (1.14)

[1] Mean of ^{14}N Townsville stylo, ^{14}N sorghum straw and nil residue treatments
[2] Standard error on parentheses

Table 5. Total recovery (%) of ^{15}N-labelled fertilizer at different growth stages of grain sorghum from N applied to 0.25 m^2 microplots of Tindal clay loam (Experiment 2)

	Recovery of ^{15}N applied			
	Tops	Roots	Soil	Total
Initiation	26.0 (2.9)[1]	0.5 (0.2)	59.4 (2.9)	85.9 (5.9)
Anthesis	34.7 (2.5)	0.6 (0.2)	42.6 (5.0)	77.9 (6.8)
Maturity	23.7 (3.4)	0.6 (0.1)	40.0 (2.3)	64.4 (4.8)

[1] Standard error in parentheses

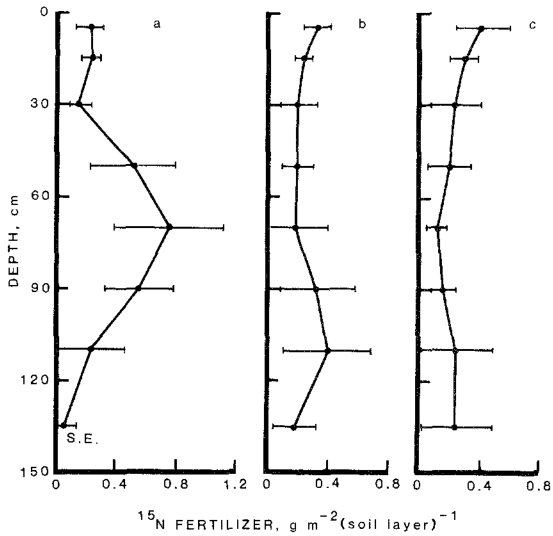

Figure 2. Profiles of ^{15}N labelled-N derived from ammonium nitrate fertilizer taken at three stages of growth of grain sorghum in a red earth at Katherine, N.T.: (a) floral initiation, (b) anthesis, (c) maturity. Each point is the mean of three residue treatments

study. Nitrogen derived from fertilizer moved very rapidly down the soil profile, much of it to beyond the effective rooting depth of grain sorghum in this soil [27, 17]. Through the use of fertilizer labelled with ^{15}N it is now possible to look for reasons for poor crop recovery of the nitrogenous fertilizer. There are two areas of concern. Firstly, the total apparent loss from the soil-plant system was quite high – increasing from 14% of the fertilizer applied at floral initiation, to 22% at anthesis and finally to 36% at crop maturity. It was previously concluded from non-tracer studies that losses of N by denitrification or volatilization of ammonia are negligible in this soil [18]. These results question that conclusion. The losses were either due to dentrification, volatilization of ammonia or leaching of nitrate. Since the fertilizer was banded below the seed, volatilization of ammonia from the soil surface is unlikely. However, 14% of the applied N was apparently lost within the first few weeks when the soil was periodically waterlogged. Denitrification is the likely pathway for this loss. Leaching of nitrate beyond 150 cm depth was not measured, but extrapolation of the graphs in Figures 2a and 2b suggests no significant leaching losses before floral initiation or anthesis. The graph in Figure 2c for crop maturity cannot be extrapolated with any confidence. To speculate on a 'worst possible' case, if the lower three points on the curve in Figure 2c represented the top half of a nitrate bulge, then approximately 12% of the fertilizer N could possibly be below 150 cm, and thus the maximum possible leaching loss is only one-third of the total observed loss. Between anthesis and maturity, the total loss from the system was 12.5%, most of which apparently was lost from the plants, rather than from the soil. It has been suggested that such losses may be largely caused by gaseous loss as ammonia and oxides of nitrogen [25]. In this experiment, losses through physical removal of plant parts (i.e. senescence, bird or insect damage) were observed to be trivial. It is also unlikely that plant N could have been lost to the soil from roots, mineralized then denitrified during the drier period between anthesis and maturity. Thus the possibility remains that the observed loss after anthesis, being one-third of the total loss, was via gaseous exchange with the atmosphere. Similar losses for grain sorghum have been reported previously [9, 19].

The losses of N from this red earth appear to be greater than those from the cracking clays of southern Queensland [6]. The main pathway of loss in the cracking clay was denitrification, whereas for the red earth it appeared to be a combination of several pathways.

In these experiments, the use of crop residues had little influence on the N economy of the system. Unrealistically high applications of stubble produced only small (13%) reductions in crop uptake of soil N. Lighter applications of plant residues produced no measurable effect. It has been suggested [26] that cereal stubble decomposing in the soil leads to a temporary decrease in soil nitrate followed by a release of nitrate later in the season. Leaching of nitrate early in the season is minimized and the late release coincides with greatest plant demand. There are three problems with this hypothesis. Firstly, very large quantities of residues would appear to be required to immobilize the nitrate. Secondly, seasonal conditions will be important, since dry soil conditions may delay either the immobilization or the remineralization of N, so that the cycle is not complete within the crop's growing period. Thirdly, it has been shown elsewhere [10] that a large proportion of immobilized N is quickly stabilized into the soil organic matter and only limited amounts (30%) are remineralized even after 160 days. Immobilization and remineralization of N, while conserving N in the system, may not be an effective supplier of N to plants, and not of any practical value in increasing fertilizer efficiency.

Substantial quantities of soil and fertilizer N were leached beyond the effective rooting depth of grain sorghum, in agreement with the observations of Wetselaar [28] and Day [7]. Although much of this nitrate was still recovered in the soil down to 150 cm, in the absence of plant uptake from that layer, it would be leached further in subsequent seasons. Thus the estimate of one-third of the total loss as due to leaching will eventually increase. If all the nitrate between 100 and 150 cm is considered as lost then the total loss is one-third greater, and the leaching loss is half the total loss. Losses of this magnitude point to the desirability of deeper rooted varieties of sorghum. Alternatively, following the suggestion of Wetselaar and Norman [27], deep rooted crops such as pearl millet (*Pennisetum americanum* L.) could be alternated with the current shallow rooted crops, with the former retrieving nitrate leached below the root zone of the latter.

Some management strategies currently exist for improving N fertilizer efficiency. Several of these were discussed by Myers [15] who concluded that split application and banding offered the best prospects. The difficulties with split application are firstly that it must be broadcast and in the event of poor rains late in the growing season, may not be leached into the soil sufficiently deeply to be effective. Secondly, it is susceptible to ammonia volatization losses. Banding was used in the experiment reported in this paper, and it is suspected that at the relatively low application rate and narrow rows used, the concentration of fertilizer in the band was not sufficiently high to retard nitrification for long enough to be effective in reducing leaching and denitrification losses.

Where agriculture is practised on the red earths of northern Austrialia, zero or minimum tillage is expected to replace conventional cultivation [11]. Such a change may influence the N dynamics in the soil. It is possible that increased infiltration of rainfall may result and this may increase the rate of leaching of nitrate. Also a change in the manner of return of crop residues to the soil will affect immobilization-mineralization processes. Another result may be that possible changes in soil bulk density may affect denitrification processes. There is therefore a need for further work on the effects of reduced tillage on soil N dynamics.

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