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Applying nitrogen to grain sorghum in central Queensland: residual value and effect of fallowing and tillage practice

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Abstract

In the northern cereal belt of Australia, farmers are reluctant to apply nitrogen (N) fertilizers because of a perception that if N is added to the soil and no crop is subsequently planted due to lack of rain, the N is 'lost'. An experiment was conducted on a cracking clay soil over three seasons to compare the response of grain sorghum to N applied to the current crop *v.* N applied the previous season which was then either planted or left fallow (to simulate a missed planting opportunity). Recovery of ^{15}N-labelled fertilizer by the crop and that remaining in the soil were simultaneously determined in microplots. The effect of tillage practice [zero (ZT) and conventional (CT)] was also examined.

Sorghum grain yield responded to fresh applications of N in 1993 and 1993/94 but not 1992, reflecting the importance of timing of rainfall rather than the total amount received within the season. Applications of N to the current crop always improved yield more than equivalent amounts of N applied to the previous crop. Grain yields of plots that were previously fallowed (fallow–sorghum rotation) were higher than the combined yields of sorghum–sorghum rotations, although fallowing was an inefficient means of accumulating both water and mineral N.

Recovery of applied ^{15}N by sorghum varied from 48% in 1992 to 36% in 1993 but was not related to the overall N responsiveness of the crop. Sorghum recovered a similar proportion of ^{15}N from plots which had been fertilized and then fallowed the previous year compared to fresh applications to the current crop, despite the fallow plots having less ^{15}N in them due to losses from the previous season. Losses of ^{15}N from the soil/plant system varied markedly with year and appeared to be related to the pattern of rainfall occurring and its possible effect on denitrification.

Tillage practice did not affect grain yields or PAWC, had minimal effect on the amount of mineral N present, and little influence on the fertilizer N requirements of sorghum *per se*.

This study suggests that there is only a small residual value to subsequent sorghum crops of fertilizer N if added initially to a successful crop. However, if N is applied pre-plant and the crop is not planted, for example due to lack of planting rain, a large proportion of this N can remain available to the following crop depending on the nature of the subsequent rainfall.

Keywords: ^{15}N, N fertilizer, fallowing, grain sorghum, tillage.

Introduction

The two biggest threats to sustainable grain production in the northern cereal belt of Australia are soil erosion resulting from high intensity rainfall and declining soil fertility, particularly nitrogen (N) (Dalal and Mayer 1986). Whereas soil

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erosion can be greatly reduced by using zero tillage practices and retaining stubble cover (Freebairn and Wockner 1986*a*; Sallaway *et al.* 1988), there are few viable options for overcoming soil fertility decline. One option is to crop less frequently, but this is not environmentally sustainable in the long term. A second option is to adopt a ley farming system similar to that used in southern Australia. However, the development of this system is still in the experimental stage, especially in the central Queensland region of the cereal belt. Alternatively, grain legumes can be incorporated into the rotation, but there is little evidence that this strategy will maintain soil fertility in this region (Dalal *et al.* 1994). The final option is to use N fertilizers.

Farmers are very reluctant to use N fertilizers in central Queensland because the unreliable rainfall reduces the probability of obtaining an economic response for any one crop. A high proportion of crops (20%) fail in this region due to the lack of sufficient soil water at planting or because of insufficient in-crop rainfall after planting (G. Spackman, pers. comm.). A perception exists that if nitrogen is added to the soil (usually during the last tillage operation prior to planting) and no crop is planted or, alternatively, if a crop is planted but subsequently fails, then the fertilizer N is 'lost' from the system and this costly investment is wasted. An understanding of the fate of N after it is applied is needed to allow farmers to make informed decisions about using N fertilizer in the grain belt of central Queensland.

This study was undertaken to determine the responsiveness of grain sorghum to N fertilizer that was either added to the current crop or had been applied about 12 months earlier and the land kept fallow (to mimic a missed planting opportunity or crop failure). The fate of N added to the soil and either subsequently cropped with sorghum or left fallow was assessed using ^{15}N-labelled fertilizer. Conservation farming practices are being adopted increasingly by farmers in this region to help reduce soil erosion. Because tillage practice has been shown to affect both the capacity of the soil to supply mineral N and the crop's requirement for N (Robson and Taylor 1987; Gibson *et al.* 1992; Thompson 1992), we also examined the effects of tillage practice (zero *v.* conventional) on the N economy of sorghum.

Materials and methods

Field site and management

The experiment was conducted on an open downs cracking clay (BUg 5·2; Northcote 1979) at the Emerald Research Station (148° 09′ E, 23° 29′ S) in the Central Highlands of Queensland. General properties of this shallow (45–80 cm depth to decomposing basalt), self-mulching clay soil (0–10 cm depth) are total N (0·086% N), organic carbon (0·97%), pH 1:5 soil/H_2O (8·1) and 0·5 M $NaHCO_3$ extractable P (19 μg/g). This soil type is typical of the majority of cropping soils in the Central Highlands, having been continuously cropped for more than 30 years. Following the harvest of a wheat crop in 1991, tillage treatments consisting of conventional (referred to as CT and achieved using chisel plough plus harrows) or zero (ZT, using chemical fallowing) tillage were imposed. Glyphosate, 2,4 D amine and ester, and atrazine were used for weed control in ZT treatments.

Experimental design

The experiment consisted of a split-split-split block design replicated four times. Each block (12 m wide × 104 m long) was split lengthwise for the two tillage treatments, ZT or CT. Each season the datum area (24 m wide × 26 m long for each main block) was moved progressively lengthwise down each tillage block because of limitations imposed by the use of trickle irrigation. At each of the three sorghum plantings (1992, 1993 and 1993/94), eight subplots (each 3 m wide × 13 m long) were established within each tillage plot in the datum area. They were sorghum planted with five rates of applied N (0, 25, 50, 75 and 100 kg N/ha as ammonium nitrate and referred to as N0 to N100), two fallow (unplanted) plots to which either 0 or 50 kg N/ha was applied, and a plot which was retained for the ^{15}N experiment. The ^{15}N plot was subsequently split into planted or fallow microplots. Where sorghum was planted after sorghum, the treatment is referred to as sorghum–sorghum rotation. Alternatively, sorghum planted into either of the two plots kept fallow during the previous crop is referred to as the fallow–sorghum rotation.

Irrigation within crop was applied to the datum area only (i.e. the eight new sub-subplots plus the eight sub-subplots from the previous crop), whereas the remainder of the blocks, which were planted to sorghum, were maintained under rainfed conditions. Consequently, there was not true randomization of treatments when comparing between years. However, measurements of soil mineral N and water at each planting revealed no significant differences between the new datum area and the N0 planted subplots from the previous crop so the data were treated as fully randomized for the purpose of statistical analysis.

Crop management

Sorghum (*Sorghum bicolor*) was planted on 75 cm row spacing and hand-thinned to 75 000 plants/ha. The cultivar Gunsynd was planted on 28 January 1992, MR40 on 18 January 1993, and Sprint on 11 October 1993. Severe drought conditions experienced in central Queensland during the project made it necessary to spray irrigate to allow planting in 1992 and in spring 1993. No further irrigation was applied to the 1992 crop. Sufficient irrigation was applied in-crop in 1993 to achieve some grain production, whereas the 1993/94 crop was irrigated to ensure average to high yields using drip irrigation lines. Details of rainfall and irrigations during the trial period are presented in Fig. 1.

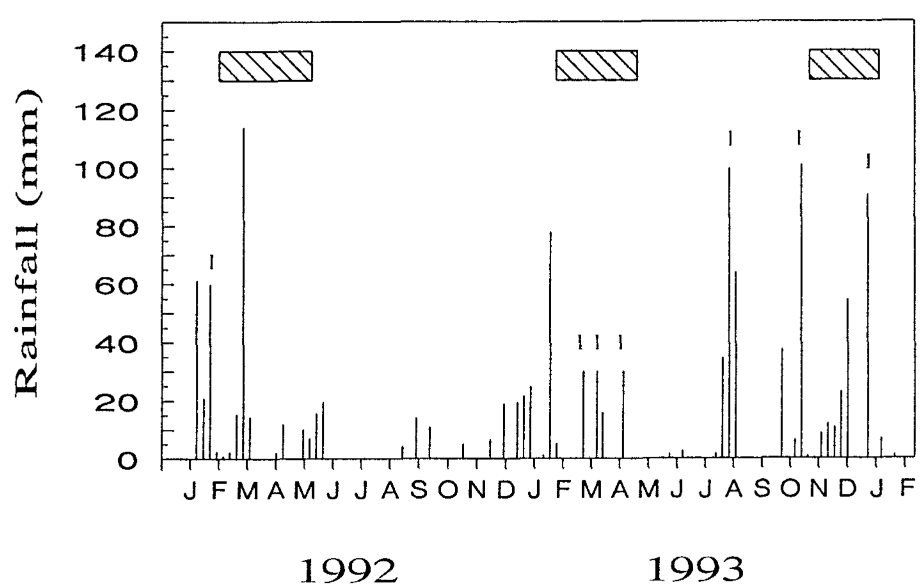

Fig. 1. Weekly rainfall and irrigation events at Emerald Research Station between 1992 and 1994. Hatch area, period of cropping; I, irrigation event.

Basal applications of 12 kg P/ha (as triple-phosphate, 19·2% P) and 2 kg Zn/ha (as zinc monohydrate, 35% Zn) were banded along side the seed at planting. Nitrogen was applied through a belt applicator and was banded next to the seed at planting. Insect control was necessary in 1992, using 'Larvin' (thiodicarb) for midge control and 'Lannate plus Dipel ES' (methomyl and *Bacillus thuringiensis*) for control of *Heliothus*.

Data collection

At planting, anthesis and grain maturity, water and mineral N contents of soil were determined for selected treatments. Three 3·75 cm diameter cores (divided into 10 cm increments to 30 cm and then 15 cm increments to decomposing basalt) were bulked from the datum area where the next crop was to be planted, whereas two cores were taken from the planted N0 and N50 and the fallow N0 treatments at anthesis and grain maturity for both mineral N and soil water. Soil mineral N samples were dried at 40°C prior to grinding (<2 mm sieve). Dry weight of shoots was estimated at anthesis and maturity by sampling 1 m of the middle two rows of each plot. At the maturity sampling, grain was separated from the stover after drying (60°C). Both components were then weighed, ground (<2 mm sieve) and retained for chemical analysis.

^{15}N study

The day after sorghum planting, microplots 2·4 m (1992) or 1·6 m (1993) long × 1·5 m wide (i.e. two row widths) were established in the ^{15}N subplots (planted and fallow) by inserting 15 cm wide tin plate 10 cm into the soil, leaving 5 cm above the ground to prevent surface water running on/off the microplots. In the microplots ^{15}N-enriched ammonium nitrate (equivalent to 50 kg N/ha at *c.* 5% atom excess, double-labelled) was placed in a band (5 cm deep) adjacent to each row of sorghum. Sorghum surrounding the planted microplot was treated with the same rate of non-labelled fertilizer. At grain maturity, 1 m lengths of both rows in the planted microplots were harvested. The rows adjacent to both sides of these microplots were also harvested to determine if they had taken up ^{15}N inside the microplot. Within both the planted and fallow microplots, all the soil from a 0·4 m length of the plot (i.e. across the 1·5 m width of the plot) was excavated in 10 cm increments to 30 cm depth. The soil was mixed and a subsample taken. The remaining depths to basalt were sampled by taking six cores in 15 cm increments and pooling. The moisture content was determined prior to oven drying (40°C for several days) and grinding to pass through a 0·5 mm sieve. In 1992, there was several weeks' delay between sorghum harvest and excavation of the microplots during which 36 mm of rainfall occurred.

The amount of ^{15}N-labelled N recovered by the crop or soil was calculated (Strong *et al.* 1992) as follows:

$$\%\text{applied N} = \%\text{N} \times \text{M} \times {}^{15}\text{N}_\text{s}/N_\text{fert} \times {}^{15}\text{N}_\text{fert} \qquad (1)$$

where % applied N is the proportion of the applied ^{15}N recovered by the plant or in the soil, %N is the N concentration (%) of the soil or plant; M is the mass of soil (g/m^2·10 cm) or plant (g/m^2), $^{15}N_s$ is the atom % excess ^{15}N in the soil or plant sample corrected for background ^{15}N, N_{fert} is the rate of fertilizer N applied (g/m^2) and $^{15}N_{fert}$ is the atom % excess ^{15}N in the fertilizer.

In 1992, the amount of soil excavated was estimated, taking the average of weights of soil excavated from the ^{15}N plots in 1993 and 1993/94. Due to the extreme difficulty of attempting to extract roots from these high clay soils (>70% clay), calculations of ^{15}N uptake by the crop did not include N in the roots.

Chemical analysis

Soil mineral-N (NO_3^- and NH_4^+) concentrations were determined by automated colorimetric analysis (Crooke and Simpson 1971; Best 1976) following extraction in 2 M KCl at a soil : extractant ratio of 1 : 10 (Bremner 1965*b*). Total amounts of mineral-N on an area basis (kg N/ha) were estimated by correcting concentrations for bulk density, measured at the termination of the trial. Bulk density was estimated for both tillage treatments when the soil was at the upper storage limit (D. Yule, pers. comm.). Sorghum grain and stover were dried, ground and analysed for total N after Kjeldahl digestion (Bremner 1965*a*). The ^{15}N content of soil and plant samples was measured using the thiosulfate modification of the Kjeldahl digestion (Dalal *et al.* 1984) and the digests were distilled according to Buresh *et al.* (1982). The distillates were then analysed on a VG ISOGAS SIRA10 dual inlet mass spectrometer.

Statistical analysis

Data were analysed with GENSTAT. Grain and N uptake data were subjected to analysis of variance with the effect of tillage practice, N rate, and year of fertilizer application partitioned into linear and quadratic components after accounting for block effects.

Results

Growth responses

Sorghum growth and grain yields were generally highest for the 1993/94 crop and lowest for the 1993 crop (Fig. 2). Whereas there was no significant ($P > 0{\cdot}05$) response to N application in 1992, both crop dry matter and grain yield responded to applied N in 1993 and 1993/94. Tillage did not significantly ($P > 0{\cdot}05$) affect either dry matter production at maturity (data not presented) or grain yield in any crop.

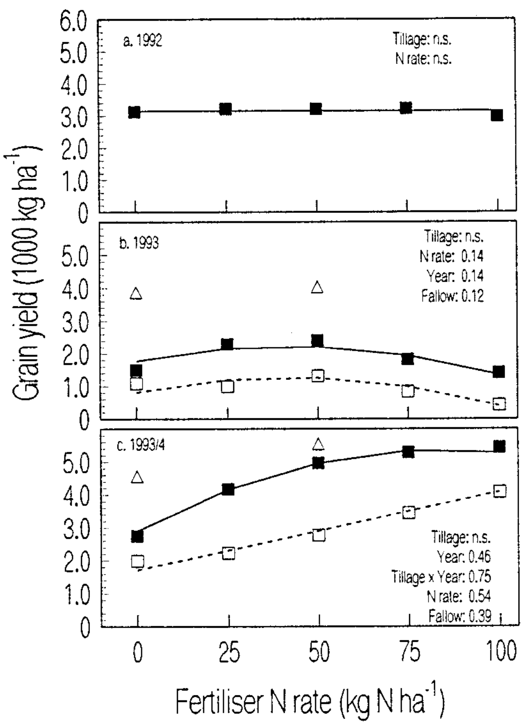

Fig. 2. Effect of current and residual fertilizer N and tillage practice on grain yield of sorghum for (*a*) 1992, (*b*) 1993 and (*c*) 1993/94. Values following factors listed for each crop are l.s.d. ($P = 0{\cdot}05$). n.s., not significant. Lines represent the best fit regression and symbols the actual data. Residual N, --□--; current N, -■-; previously fallowed, △. Best fitting models, where N = kg N ha^{-1} and values in parentheses are the standard error of the estimate, for each treatment were: (*a*) 1992 Yield = 3151 (±104) (not significant) (*b*) 1993 Yield 92 = 817 (±206)+21·8 (±7·4) N −0·26 (±0·07) N^2; Yield 93 = 1770 (±206)+21·8 (±7·4) N −0·26 (±0·07) N^2; (*c*) 1993/4 Yield 93 = 1710 (±142)+23·8 (±2·38) N; Yield 94 = 2894 (±131)+58·8 (±14·2) N −0·35 (±0·14) N^2.

The timing of application of N always affected yield. Fertilizer N applied to the current crop produced higher grain yields compared to the N applied to the previous crop (residual N). In 1993, grain response to N applied to the previous crop was directly proportional to the response to N applied in the current season. In 1993/4, grain response asymptoted to N application between 50 and 75 kg N/ha, whereas there was a linear response to the highest rates of N applied the previous year. The largest crop response to residual N was in the 1993/94 crop.

Fallowing the previous year resulted in significantly higher grain yields where no N was added. Adding 50 kg N/ha in 1992 prior to fallowing did not significantly affect the following crop compared to the N0 fallow, whereas adding N to the 1993 fallow resulted in significantly greater yields of dry matter and grain in the 1993/94 sorghum crop. Fallowing in 1992 produced higher yields in the 1993 sorghum crop than even the highest yielding sorghum–sorghum N treatment. The 1993 fallowed N0 treatment produced the same yield in the 1993/94 sorghum crop as adding between 25 and 50 kg N/ha in 1993/94 where sorghum had been previously planted.

N uptake

Total sorghum (shoot plus grain) N at grain harvest increased significantly ($P < 0{\cdot}01$) with increasing rate of N fertilizer in all years (1992, 1993, and 1993/94) but was unaffected by tillage practice (Fig. 3). Nitrogen uptake was always higher when N was applied to the current crop compared with N applied to the previous crop. Fallow–sorghum plots had significantly higher N uptake by the sorghum regardless of whether N fertilizer had been added or not compared to sorghum–sorghum plots. For example, N0 plots fallowed in 1992 had higher crop N uptakes than fresh applications of 100 kg N/ha made to the 1993 sorghum crop.

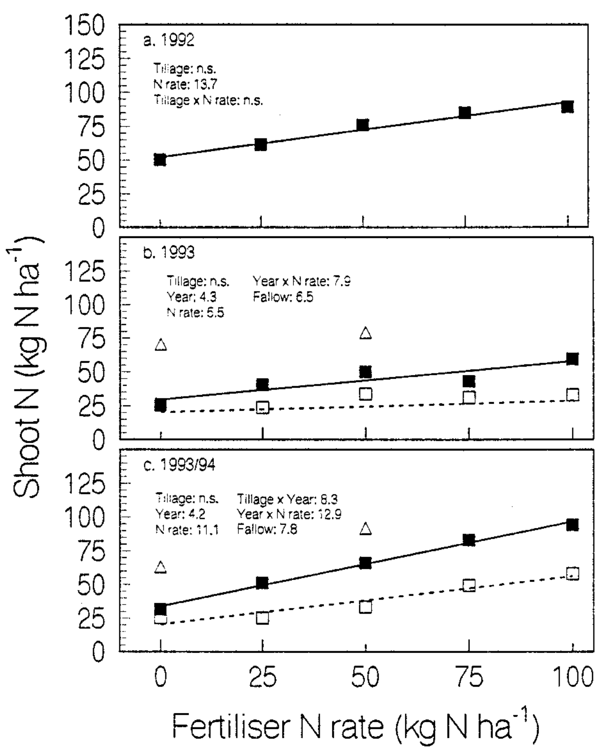

Fig. 3. Effect of current and residual applications of N and tillage practice on shoot N (grain plus straw) of sorghum for (*a*) 1992, (*b*) 1993 and (*c*) 1993/94. Symbols as in Fig. 2. Equations for each treatment were: (*a*) 1992 $Nupt = 52{\cdot}1\ (\pm 3{\cdot}6) + 0{\cdot}41\ (\pm 0{\cdot}059)\ N$; (*b*) 1993 $Nupt92 = 20{\cdot}2\ (\pm 2{\cdot}4) + 0{\cdot}086\ (\pm 0{\cdot}04)\ N$; $Nupt93 = 29{\cdot}5\ (\pm 2{\cdot}4) + 0{\cdot}284\ (\pm 0{\cdot}04)\ N$; (*c*) 1993/4 $Nupt93 = 20{\cdot}4\ (\pm 3{\cdot}7) + 0{\cdot}36\ (\pm 0{\cdot}07)\ N$; $Nupt94 = 33{\cdot}8\ (\pm 3{\cdot}7) + 0{\cdot}63\ (\pm 0{\cdot}07)\ N$.

Harvest indices for N uptake (N content of grain as a proportion of N of whole tops) were unaffected by either tillage or rate of fertilizer N in 1992, but mirrored patterns of N uptake in 1993, *viz.* decreasing with increasing rate of N fertilization with higher values for N applied to the current crop compared to residual applications (data not presented).

Fertilizer N uptake was calculated indirectly (FUE) as the difference in shoot N uptake between fertilized and unfertilized (control) treatments divided by the amount of fertilizer applied. FUE was not affected by tillage treatment but decreased significantly ($P < 0{\cdot}05$) as the fertilizer rate increased, ranging from 61% at 25 kg N/ha to 45% at 100 kg N/ha (data not presented). FUE ranged from an average across tillage treatments of 51 in 1992, 49 in 1993, and 69% in 1993/4 (Fig. 4).

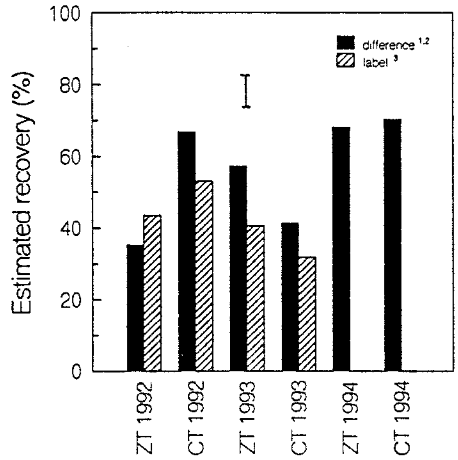

Fig. 4. Estimated recovery of N fertilizer (applied at 50 kg N/ha) by sorghum shoots under both zero (ZT) and conventional (CT) tillage using both the difference and ^{15}N methodologies in 1992 and 1993. [1] [Crop N uptake (N50) −Crop N uptake (N0)]/N rate (=50) × 100. [2] Effect of year, tillage and year × tillage not significant ($P > 0 \cdot 05$). [3] Bar represents l.s.d. ($P = 0 \cdot 05$) for ^{15}N values. No ^{15}N data were collected for the 1993/94 crop.

Soil water

The plant available water content (PAWC) of fallow plots was always higher than of planted plots during crop growth (Fig. 5). At the time of planting of the 1993 crop, plots kept fallow during the previous year contained more PAWC (average 27 mm) than plots planted in 1992. Previously fallowed plots did not contain any more soil water than planted plots at planting time for 1993/94 due to the large amount of irrigation applied pre-plant.

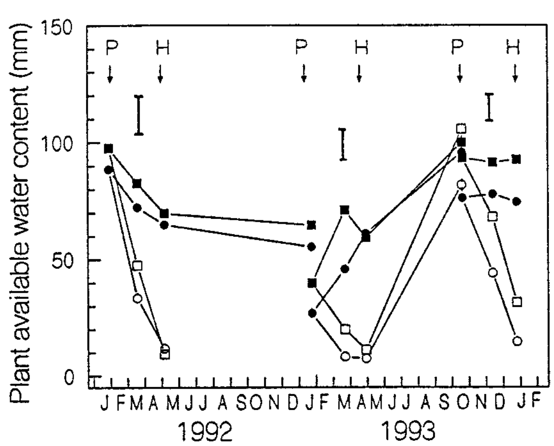

Fig. 5. Changes in plant-available soil water content (PAWC) of the profile (to decomposing basalt) in the sorghum crop and concurrent fallow plots under zero and conventional tillage practices during the study period. ZT fallow N0,–■–; CT fallow N0, –●–; ZT planted N0, –□–; CT planted N0, –○–; P, planting; H, harvest. Bar represents l.s.d. ($P = 0 \cdot 05$) for the period between planting of one crop and planting the next crop for the 1992, 1993 and 1993/94 crops.

Tillage practice did not significantly ($P > 0 \cdot 05$) affect PAWC of the soil profile either at planting or during crop growth in any year (Fig. 5). Significant decreases ($P < 0 \cdot 05$) in the PAWC of planted plots occurred between anthesis and maturity in the 1992 and 1993/94 crops, but in 1993 PAWC was already low by anthesis and remained so until grain maturity. PAWC remaining in sorghum plots where N had been added did not significantly ($P > 0 \cdot 05$) differ from N0 plots at grain maturity (data not presented).

Accumulation of mineral N

Mineral N (NO_3^-+NH_4^+) present at planting was generally low for all sorghum–sorghum rotations, ranging from 52 in 1992 to 35 kg N/ha for the short fallowed 1993/94 spring sorghum crop (Fig. 6). Keeping plots fallow the previous season resulted in significantly higher mineral N ($P < 0 \cdot 05$) at planting in 1993 (average increase of 92 kg mineral N/ha) compared to sorghum–sorghum crops, but there was little effect of fallowing in 1993 at planting in 1993/94.

Tillage practice did not affect the amount of mineral N present at planting or during crop growth in sorghum–sorghum treatments in any year (Fig. 6). Where plots had been previously fallowed, mineral N at planting time was higher in CT than ZT treatments in 1993, but there was no significant tillage effect in 1993/94.

In plots previously planted to sorghum, there was no clear trend in the amount of mineral N present during the crop (Fig. 6). In 1992, mineral N remained unchanged between anthesis and crop maturity. In 1993, mineral N decreased significantly during the corresponding period, whereas in 1993/94 the rate of mineral N accumulation exceeded the crop's ability to absorb N. In both 1993 and 1993/94, a significant amount of mineral N (25 to 30 kg N/ha) still remained in the soil at grain harvest even in unfertilized plots.

Mineral N also varied erratically in fallow plots with time (Fig. 6). In 1992, the amount of mineral N present did not differ significantly ($P > 0{\cdot}05$) between planting and crop maturity, whereas in the other years it increased. Notably, mineral N decreased in plots kept fallow between anthesis and maturity in 1993.

Tillage practice did not significantly ($P > 0{\cdot}05$) affect the distribution of nitrate in the soil profile (data not presented). There generally appeared to be little leaching of nitrate, even in fallow plots. The one exception appeared to occur in the 1992 fallow treatment between anthesis and maturity.

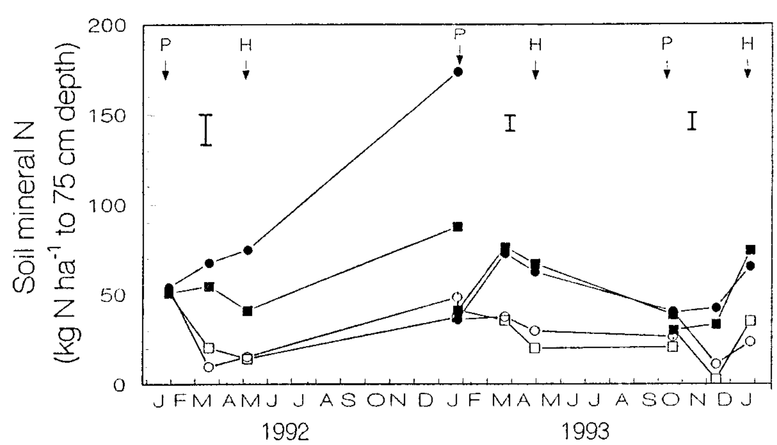

Fig. 6. Changes in soil mineral N ($NH_4^+ + NO_3^-$) in the soil profile during the study period. Symbols as in Fig. 5.

^{15}N study

With the exception of one microplot (a plot previously kept fallow), less than 5% of the applied ^{15}N was recovered in buffer row plants, indicating that there was little lateral movement of the label or accession by plants outside the microplot.

Recovery of ^{15}N by the above-ground crop (grain plus straw) was significantly higher ($P < 0{\cdot}05$) in 1992 (average of 48% of the added N) than for the 1993 crop (36%) (Fig. 7). Tillage practice did not significantly ($P > 0{\cdot}05$) affect ^{15}N recovery by sorghum in either 1992 or 1993. In 1993, sorghum grown on plots which were fallowed and fertilized in 1992 recovered a similar proportion of the 1992 applied ^{15}N compared to when ^{15}N was first applied to the 1993 sorghum for each tillage practice. Only a small proportion of the ^{15}N applied to sorghum in 1992 (4·8 to 7·5%) was recovered by the following 1993 sorghum crop.

When data were pooled (planted+fallow treatments), the total recovery of ^{15}N in the plant plus soil was significantly higher in CT plots (89%) than in ZT plots (76%). In 1992, less than 20% of the ^{15}N applied that season was lost from the planted systems by grain maturity, whereas an average of 39% was lost from the equivalent fallow treatments. In 1993, losses of 1993 applied ^{15}N were significantly less in both planted (7%) and fallow (5%) treatments.

The amount of ^{15}N detected in the soil below 20 cm varied markedly between 1992 and 1993. In 1992, the added ^{15}N present in the 20–60 cm soil layer was 12·4% for the CT fallow and 8·2% for the ZT fallow (data not shown). There was no indication of ^{15}N movement below 60 cm, which is the average depth to decomposing basalt in this soil. In 1993, there was little detectable movement of ^{15}N below 20 cm in the fallow treatments when sampled at grain maturity. In planted treatments, little of the added ^{15}N was found below 20 cm in either 1992 or 1993.

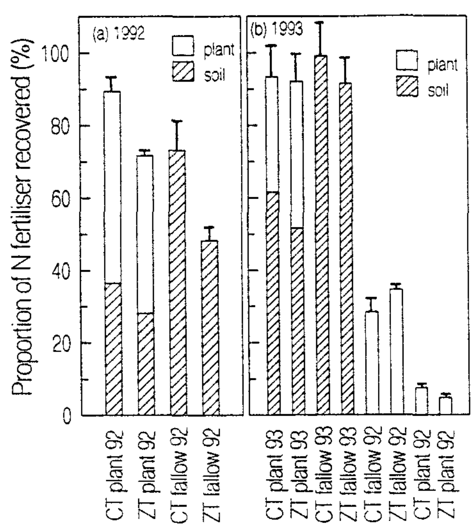

Fig. 7. The proportion of ^{15}N added to the soil at planting recovered in above-ground sorghum or remaining in the soil at crop maturity in sorghum–sorghum or fallow–sorghum rotations for (*a*) 1992 and (*b*) 1993. Residual ^{15}N in the soil was not measured in 1993. Bars are the standard error of mean.

Discussion

Growth responses to N

Despite the low N status of the shallow open downs soil used in these experiments, the uptake of N applied both to the current crop and that applied previously depended heavily on soil water content and to a lesser extent the amount of soil mineral N present. The yield of sorghum without added N reflected the amount of PAWC and mineral N present at planting. However, the response to added N appeared to be related to the timing of rainfall rather than the summation of the total soil water availability during crop growth. For example, the 1992 crop received 140 mm between planting and anthesis (Fig. 1), but the lack of any further significant in-crop rainfall after anthesis meant that the crop was unable to reach its yield potential, thus reducing the responses to N. In contrast, the 1993 crop had lower soil moisture at planting and less in-crop rainfall (despite three small irrigations), but still responded significantly to applied N. Nix and Fitzpatrick (1969) and Holland and Herridge (1992) have noted that the timing of rainfall, particularly around flowering, is critical to sorghum grain yields in the northern cereal belt.

^{15}N study

The recovery of fertilizer N by the sorghum in this experiment compared well to other studies in this region. Sorghum recovered an average of 48% of the 50 kg N/ha applied at planting in 1992 but only 36% in 1993 based on the ^{15}N data. If N contained in the roots is included, these values could be increased by a further 9 to 13% (Rao *et al.* 1992). Other studies of crop recoveries of ^{15}N fertilizers conducted on the Vertisols of the northern cereal belt have generally ranged between 38 and 65% for wheat (Craswell and Strong 1976) and between 37 and 50% for sorghum (Myers and Hibberd 1986; Strong *et al.* 1992). In common with these previously published studies, soil water strongly influenced results in the current experiment with the best crop recovery occurring in the wetter 1992 (before flowering) compared to the overall drier 1993 crop. However, crop recovery of ^{15}N was not related to the overall responsiveness of the crop to N fertilizer as no significant response to N was found in the 1992 crop (Fig. 2).

Despite allowing better utilization of fertilizer N by the crop itself, the period of good soil moisture between planting and anthesis in 1992 (due mainly to a 110 mm rainfall event, Fig. 1) also coincided with significant losses of ^{15}N from the soil/plant system. Although these losses were significant in the planted system (*c.* 20%), they were greatest in the fallow treatment (39%). In contrast, PAWC was much lower during this period for the 1993 crop, due to lower PAWC at planting and the absence of any effective rain, and less than 7% of the ^{15}N was unaccounted for. This positive relationship between these losses of ^{15}N and both high PAWC and mineral N suggests that denitrification caused this loss of N (Aulakh *et al.* 1992). There was little evidence of leaching of N down the soil profile in either the ^{15}N or mineral N data, although this may reflect movement of N into the decomposing basalt layer which was not sampled. In 1992 a large rainfall event soon after planting may have resulted in pronounced denitrification. All the fertilizer N would have nitrified and both soil water and mineral N concentrations would have been high as there had been little opportunity for depletion by the young crop, thus providing ideal conditions for denitrification. In contrast, PAWC increased only after anthesis in 1993 by which time the ^{15}N had either been utilized by the crop or incorporated into organic forms such as biomass N in the fallow treatments, thus minimizing its susceptibility to both leaching and denitrification. Strong *et al.* (1992) have also found a strong correlation between the amount of rainfall (or irrigation) and losses of fertilizer N, which they have attributed to denitrification, in cracking clay soils in this region.

As in numerous other studies (Westerman and Kurtz 1972; Ladd and Amato 1986; Strong *et al.* 1987; Hart *et al.* 1993), only a small proportion (less than 7%) of the ^{15}N added to the first crop was recovered by the subsequent crop. However, the 1993 sorghum recovered similar quantities of ^{15}N from applications made to both the current crop and from that applied 12 months previously and subsequently kept fallow until planting of the current crop (Fig. 7). In central Queensland there is a high probability that no crop will be planted after fertilizer N is applied to the soil (which is usually in the last tillage operation prior to an anticipated planting) or that if a crop is sown, the crop will fail due to insufficient follow up rainfall. The high recovery by sorghum of ^{15}N added to a fallow the previous year (which simulated a missed planting opportunity) occurred despite loosing up to 39% of the ^{15}N in these plots prior to sampling the previous July (Fig. 7). More of this ^{15}N may have been subsequently lost in the period prior to planting in January 1993, due to the high soil water in the fallow and hence higher potential rates of denitrification or leaching (Aulakh *et al.* 1992). Consequently, this previously applied ^{15}N was more effectively used than fresh applications made in 1993. Unfortunately, no measurement was made of ^{15}N-labelled mineral N in this study to determine how much of the ^{15}N in the fallow plots was readily available to the following crop. However, this result does not appear to result from isotopic exchange as there was generally good agreement between the difference method and ^{15}N labelling (see Table 1 and Figs. 2 and 7). The better utilization of the ^{15}N in these previously fallowed plots by the following sorghum was probably due to the relatively good soil water supply at planting compared to the previously cropped plots (Fig. 4). However, leaching of this ^{15}N from its original placement at 5 cm to deeper in the profile (10–20 cm) may have also enhanced its availability to the sorghum.

There was a general agreement between the estimates of crop recovery of N based on difference methods and ^{15}N labelling (Fig. 4), although the indirect comparison generally gave higher recoveries of N. The difference method is generally regarded as giving higher values than isotopic methods but also tends to be much more variable, especially when the responsiveness to the applied N is small, such as in 1992 (Roberts and Janzen 1990). However, as Rao *et al.* (1992) note, neither method can be considered better than the other.

Table 1. Net rate of nitrogen accumulation (kg N/ha·day) during the crop and between crops in relation to tillage practice and fallowing over 3 years at Emerald

CT, conventional tillage; ZT, zero tillage. Values are mean (±s.e.m.) N accumulation in the planted treatment includes N contained in the above-ground plant (but not N contained in roots)

Treatment	Period for soil N accumulation				
	1992 crop	1992/93 fallow	1993 crop	1993 fallow	1993/94 crop
Period	28/1–5/5	5/5–18/1	18/1–23/4	23/4–11/10	11/10/93–10/1/94
Fallow CT	0·21 (0·02)	0·38 (0·06)	0·27 (0·03)	−0·13 (0·03)	0·28 (0·06)
Fallow ZT	−0·10 (0·07)	0·18 (0·08)	0·27 (0·07)	−0·17 (0·05)	0·48 (0·11)
Planted CT	0·10 (0·06)	0·11 (0·01)	0·21 (0·05)	−0·02 (0·03)	0·18 (0·07)
Planted ZT	0·16 (0·07)	0·08 (0·03)	0·04 (0·04)	0·003 (0·02)	0·38 (0·04)

Effect of fallowing

When compared on a cropping sequence basis, the combined yield of the sorghum–sorghum rotation still yielded 49% less than the fallow–sorghum rotation in 1993 and 31% in 1993/94 when no N was applied. The beneficial effect of fallowing appeared to be due to enhanced soil water rather than soil N supply. Fallow–sorghum treatments contained an extra 27 mm of PAWC compared to sorghum–sorghum treatments at planting in 1993. Even if enough N fertilizer was added to remove N deficiency (i.e. 50 kg N/ha in 1993), the fallow–sorghum rotation outyielded the sorghum–sorghum rotation by 45%. Only in 1993/94 at the highest rate of N fertilizer (100 kg/ha) did the sorghum–sorghum rotation yield better (by 24%). This contrasts with southern regions of the northern cereal belt where fallowing has been shown to produce little yield advantage when compared to short (6 months) fallowing into sorghum, especially at moderate to high fertility sites (Herridge and Holland 1992).

Despite the apparent yield advantage, fallowing was still an inefficient means of accumulating both limited rainfall and mineral N. For example, there was little net accumulation of mineral N between harvesting the 1993 crop and planting of the 1993/94 crop (Fig. 6) and there was actually a net decrease in the amount of mineral N in the fallowed treatments. The losses of mineral N in the intercrop fallow coincided with two large irrigation events (100 mm each) prior to planting in October 1993 and it is likely that these losses were due to denitrification (see earlier discussion in ^{15}N section). Opportunity cropping (as opposed to set fallows) is being increasingly adopted by grain growers in this region due to the potentially higher number of planting opportunities it affords growers. Our results also indicate that although opportunity cropping may result in lower rates of N mineralization (due to lower PAWC during fallows; see following section), it will help to minimize net losses of soil N and water. However, the potential benefits of opportunity cropping will only be fully achieved if soil fertility is adequate. This higher fertility may be achieved either through the use of fertilizers or possibly legume rotations (Holland and Herridge 1992).

N accumulation

Net rates of N accumulation during the intercrop fallows (previously planted) were low ranging from an average across tillage treatments of 0·10 kg N/ha·day for the 1992 to 1993 fallow to net negative values between the 1993 and 1993/94 crops (Table 1). These accumulation rates were significantly increased in plots kept fallowed, reflecting the strong positive influence of soil water (Myers *et al.* 1982) rather than time per se on N mineralization for this basaltic clay. An 'average' yielding sorghum crop in central Queensland of 1·5 t/ha at 10% protein and a harvest index of 0·55 (it ranged from 0·45 to 0·70 during the trial) would require at least 44 kg N/ha. With an average fallow length of 265 days for a sorghum–sorghum rotation, mineralization would produce 27 kg N/ha, indicating the need to apply some fertilizer N to achieve at least average yields. Unfortunately, the net rates of N accumulation were highly variable reflecting the varied nature of fallow rainfall and errors associated with measurement of soil mineral N. This makes predictions of crop requirements for fertilizer N difficult even if the availability of soil water to the crop, and hence yield potential, can be accurately estimated. This problem highlights the need for a predictive model where farmers can calculate likely N accumulation rates based on the amount and frequency of rainfall and soil type for a particular paddock. The generally low N accumulation rates of this soil become even more critical when double cropping (i.e. short fallow) or if mineral N is lost such as occurred between the 1993 and 1993/94 spring sorghum crop.

Effect of tillage practice

Tillage practice did not affect the yield of any crop. Zero tillage practices generally have been found to result in higher soil water content in central Queensland farming systems during below average rainfall years (Thomas *et al.* 1990), thereby resulting in higher demand for N by the crop (Radford, pers. comm.). The lack of any significant effect of tillage practice on yields in this experiment probably reflects the nature of precipitation (poor intercrop fallow rainfall and the use of irrigation to enable planting in both 1992 and the 1993/94 spring crop). Zero tillage tends to result in less runoff during fallows and therefore greater rainfall infiltration during high intensity rainfall events (Freebairn and Wockner 1986*b*). During the period of this experiment, most rainfall events during the fallows were of only moderate intensity (<10 mm/h) so that the increased stubble loads in ZT treatments had no effect on PAWC at planting. Despite the general expectation that reduced tillage practices would decrease the amount of mineral N, as implied in other studies in this region (Dalal 1989; Standley *et al.* 1990), there appeared to be little general effect on N mineralization rates during fallowing; only for the 1992 incrop fallow treatments did mineral N increase significantly more in CT than ZT treatments.

Conclusion

As the length of time of continuous cropping on the cracking clay soils of central Queensland increases, soil fertility will decrease and grain crops such as sorghum will increasingly respond to fertilizer N (Garside *et al.* 1992). Tillage practice appears to have little influence per se on the N requirements of sorghum, although seasons where ZT lead to higher PAWC at planting will require higher rates of fertilizer N. Because rainfall is unreliable in this region, it is difficult to predict fertilizer N requirements for any particular crop. In our experiments, however, we found that if fertilizer N is applied but the crop cannot be planted in the immediate future, a high proportion of this N can remain in the soil for the next crop. However, the residual value of this fertilizer N will depend on the following rainfall patterns and their effect on potential losses of N by denitrification.

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