*Aust. J. Agric. Res.*, 1996, **47**, 695–703

# Nitrogen fertiliser residues for wheat cropping in subtropical Australia

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*Abstract*

Applied nitrogen (N) recovered by fertilised wheat and by successive wheat crops in a 4-crop sequence (1987–90) was studied by applying $^{15}$N-depleted ammonium nitrate (0, 2·5, and 7·5 g/m$^2$) to a Vertisol in the summer-dominant rainfall region of northern Australia. Recoveries of applied N by each of the 4 crops in order of cropping sequence were 60·3±4·2, 4·4±2·3, 1·3±0·49, and 0·8±0·56%, there being no effect of 2 tillage treatments, conventional tillage (CT) and no till (NT), on uptake of applied N. There was very low recovery of residual fertiliser N after the first wheat crop was harvested; usually <10% of the applied N was recovered. There was evidence of a substantial N carryover benefit where fertiliser N (7·5 g/m$^2$) was applied in 1987, but not when applied at the same rate in 1988 or 1989.

Carryover effect was shown only when fertiliser N was applied after a long fallow when antecedent $NO_3^-$-N was already high (100–150 *v.* 30–55 kg/ha with a normal summer fallow). Carryover of subsoil $NO_3^-$-N from a single N fertiliser application to the crop, as occurred with application in 1987, will provide useful buffer for declining N supplies of soil N in seasons of good crop response. Routine application of N at moderate rates (<75 kg/ha) provides an effective means of supplementing declining soil N reserves for winter cereals in this region of unreliable rainfall.

*Additional keywords:* Vertisol, $^{15}$N-depleted fertiliser, monoculture, no till.

## Introduction

Because of the lack of suitable legume species and other constraints to land use, phases of ley pastures are relatively uncommon in fields used for cereal cropping in the summer rainfall region of subtropical Australia. In fact, continuous cropping for very long periods, extending to several decades with a high frequency of cereal crops in the rotation, is a common practice. Because of the heavy pressure due to crop removal of N in cereal grains, inputs of N fertilisers are now essential for these cropping systems.

The unreliable rainfall for crops may lead either to low crop use of applied fertiliser (Strong *et al.* 1986) or to reduced fertiliser efficiency (Myers 1979; Fiegenbaum *et al.* 1984) for crop production. This may cause extreme variation in responses to fertiliser, ranging from highly profitable outcomes to financial losses where responses are small or do not occur (Strong *et al.* 1992). For these reasons, application rates of N fertilisers have been quite modest (Martin *et al.* 1988).

0004-9409/96/050695$05.00

What is usually overlooked by producers, however, is that N fertiliser application may create a significant carryover effect to crops in the years after the application. This is especially true if dry conditions limit the uptake of applied N by the fertilised crop (Myers 1979; Fiegenbaum *et al.* 1984). Such responses to fertiliser N in years following the application may increase the profitability of N fertiliser use.

Rain-grown winter cereals frequently are grown following a period of fallow to allow sufficient water to be stored to have more assured grain production. Weed control during the fallow by the use of herbicides without tillage can promote more efficient water storage in the heavy clay soils of the region (Marley and Littler 1989). Thus, reduced or no till is being practised increasingly for cereal crop management. Elsewhere, when no till has been introduced into cropping systems, N management has become a limiting factor for crop production (Phillips 1982).

In humid temperate climates where fertiliser recovery has been determined in contrasting tillage systems (Kitur *et al.* 1984; Meisinger *et al.* 1985; Walters and Malzer 1990), tillage has been found to have little effect on fertiliser efficiency. Also in humid climates, recovery of residual fertiliser N in isotopic studies, in the following crops, is usually meagre (Sanchez and Blackmer 1978; Walters and Malzer 1990), rarely exceeding 5% of the original application and falling to even smaller recoveries for subsequent crops.

We measured the utilisation of soil and applied N by successive wheat crops grown in a system of continuous cropping on a vertisol in the subtropical region of Australia. Nitrogen-15 labelled fertiliser N was applied either to one crop followed by residual N uptake by successive 3 crops, or to each crop every year in a 4-year sequence of cropping between 1987 and 1990.

## Materials and methods

The experiment was conducted as a part of a larger program of N management research for fertility-degraded soils of the region (Dalal *et al.* 1995). It was located on a fertility-depleted Vertisol (Typic Chromustert) in a semi-arid region, with a mean annual rainfall of 630 mm, in subtropical Queensland (26° 47′ S, 150° 53′ E), Australia. Clay, organic C, and total N contents of the top 0·1 m of soil were 55, 0·7, and 0·7%, respectively, and its pH was 8·5.

Following a barley crop which was harvested in December 1985, very low rainfall during 1986 (397 mm) prevented wheat sowing that year. The 4-year sequence of wheat crops began in 1987.

Within each of 4 replicate blocks of a larger field experiment, an area of 4·5 m by 25 m was selected on either side of the junction between 2 tillage treatments; soil was tilled conventionally (CT) 2–4 times during the fallow, or herbicides were used to control weeds without tillage (NT). Six plots 3 m long were located end on end, with a 1-m or 3-m gap between plots, along each of two 2·25-m-wide strips within each tillage treatment.

Ammonium nitrate depleted in $^{15}$N (0·0118 atom% $^{15}$N) was applied during seeding in 4 bands 0·5 m apart using a cone seed distributor and placed approximately 7 cm deep. Each year between 1987 and 1990, fertiliser N was applied at the rate (g/m$^2$) of 0, 2·5 (25 kg/ha), or 7·5 (75 kg/ha) to plots which had received no previous fertiliser application. Two treatments received fertiliser N at the same rate annually (2·5 or 7·5 g/m$^2$) in each of the 4 years. An extra control treatment (nil fertiliser) made a total of 12 plots for each tillage type in each replicate block. Wheat seeds (cv. Hartog) were sown in 25-cm rows, 12·5 cm on either side of each fertiliser band, on the day fertiliser N was applied. Sowing and harvest dates were 30 May and 22 October 1987, 26 May and 18 October 1988, 20 June and 10 November 1989, and 3 July and 9 November 1990.

At flowering in 1988, 1989, and 1990, 10 plants fertilised with $7 \cdot 5$ g N/m$^2$ were removed at random from row 2, which was outside the plot area proposed for grain and straw harvest at maturity. The $^{15}$N content and total N of these plants were measured to estimate the proportion of fertiliser N contained in the crop. On the same day, plant dry matter yield was measured on adjacent field plots managed identically to the $^{15}$N-depleted fertilised plots except urea was used as the N source. At the centre of each plot at crop maturity, 1-m lengths of rows 4 and 5 were cut at ground level to determine the grain to straw ratio and to provide a straw sample for total N and $^{15}$N analysis. Ears were then removed from the central 2 m of rows 3, 4, 5, 6, and 7. Grain yield was determined, therefore, on an area of $2 \cdot 5$ m$^2$ by combining 2 grain samples for each plot after threshing.

Subsamples of grain and straw were dried, ground, and analysed for total N and $^{15}$N using modification of the Kjeldahl method (Buresh *et al.* 1982); $NO_3^-$-N was recovered using the reduced iron method (Bremner 1965). Steam distillates were dried and $(NH_4)_2\ SO_4{-}H_3BO_3$ salts were analysed for $^{15}$N content on a Micromass MM622 (VG Isotopes, Winsford, England) mass spectrometer. Recovery of applied $^{15}$N was calculated as follows:

$$\text{Recovery (\%)} = \frac{\%\text{N} \times \text{M} \times (^{15}\text{N}_\text{f} - ^{15}\text{N}_\text{nf})}{\text{N}_\text{fert} \times ^{15}\text{N}_\text{fert}}$$

where recovery is the percentage of the applied $^{15}$N recovered in the plant part; %N is the N concentration (%) of the plant part; M is the mass of plant material (g/m$^2$); $^{15}\text{N}_\text{f}$ and $^{15}\text{N}_\text{nf}$ are atom% excess $^{15}$N fertilised and unfertilised plants, respectively; $\text{N}_\text{fert}$ is the rate of fertiliser N applied (g/m$^2$); and $^{15}\text{N}_\text{fert}$ is the atom% excess $^{15}$N in the fertiliser.

In May, prior to sowing each wheat crop, the soil was sampled on adjacent field plots $12 \cdot 5$ m by $2 \cdot 25$ m, where fallow, crop, and N fertiliser management practices were identical to those of these smaller plots, except that urea was applied as the N source. From soil previously unfertilised with N, four 5-cm-diameter cores to $1 \cdot 2$ m were taken, one from each quarter of the plot. From previously N-fertilised soil, 4 cores were taken at equal spacings ($12 \cdot 5$ cm) along a line at right angles to fertiliser application bands. Soil cores were subdivided into $0 \cdot 1$ m depth intervals down to $0 \cdot 3$ m depth and $0 \cdot 3$ m intervals below $0 \cdot 3$ m depth and composited by depth for each plot. Soil was air-dried at 40°C under forced draught, ground to pass a 2 mm sieve, extracted with 2 M KCI at a solution to soil ratio of 10:1, and analysed for $NO_3^-$-N by an automated method (Best 1976).

Annual rainfall (mm) commencing in October, to coincide with the commencement of the fallow phase preceding the wheat crop, was 577, 853, 601, and 719 for 1987, 1988, 1989, and 1990, respectively. Rainfall received during winter months (June, July, August) in order of cropping sequence was 63, 168, 108, and 66 mm. Rainfalls for 1987 and 1990 were below the long-term average for the region (630 mm), rainfall for 1989 was similar to the average, and that for 1988 well above average.

## Results

### *Total N uptake by wheat crops*

Over the 4 successive crops, the quantity of N recovered in the grain and straw of unfertilised wheat ranged from 44 to 123 kg/ha (Table 1). In only one crop (1987) was there a significant ($P < 0 \cdot 05$) effect of tillage on crop N uptake, in which case, more N was taken up for CT (123 kg/ha) than for NT (98 kg/ha). Fertiliser application at both levels increased the quantity of N taken up by each of the 4 crops, but in some instances increases were not significant ($P > 0 \cdot 05$) at the low N rate.

Prior fertiliser application had little effect on N uptake of subsequent crops. The only significant effect of prior fertiliser application on N uptake occurred in 1988; fertiliser N applied in 1987 increased total N uptake of wheat even in the treatment which received fertiliser annually at the rate of 75 kg N/ha (CT only). The apparent residual effect of fertiliser N applied in 1987 was further demonstrated by increased N uptake in the 1988 crop where only the 1987 crop received fertiliser N; 85 kg N/ha was taken up by the crop in 1988 where 75 kg N/ha was applied to the 1987 wheat crop compared with only 64 kg N/ha where neither crop received fertiliser N (Table 1).

**Table 1. Nitrogen uptake (kg/ha) in grain and straw of wheat fertilised with $^{15}$N-depleted ammonium nitrate-N applied at 0, 25, or 75 kg N/ha on conventional tillage (CT) and no-till (NT) treatments at Warra**

Values in parentheses are N uptake for unfertilised crop following crop fertilised the previous year

| Tillage and N rate[A] | 1987 | 1988 | 1989 | 1990 |
|---|---|---|---|---|
| CT 0 | 123 | 64 | 45 | 55 |
| CT 25 | 136 | 77 (55) | 56 (39) | 68 (45) |
| CT 25A | — | 74 | 55 | 62 |
| CT 75 | 150 | 115 (85) | 98 (43) | 89 (55) |
| CT 75A | — | 144 | 95 | 93 |
| NT 0 | 98 | 54 | 44 | 55 |
| NT 25 | 116 | 73 (51) | 64 (47) | 67 (54) |
| NT 25A | — | 71 | 61 | 69 |
| NT 75 | 136 | 99 (80) | 89 (45) | 103 (60) |
| NT 75A | — | 104 | 88 | 84 |
| l.s.d. ($P = 0\cdot05$) | 17·9 | 18·9 | 11·8 | 12·0 |

[A] Fertiliser N was applied either where no fertiliser N was previously applied (25 and 75) or where fertiliser N was applied annually to each successive crop (25A and 75A).

### *Fertiliser N uptake by wheat crops*

Because the applied N was depleted in its $^{15}$N content, the quantity of applied N recovered by each successive wheat crop could be determined from isotopic analyses of plant N at flowering and at maturity.

Estimated recoveries of applied N in plant samples collected at the time of flowering of 1988, 1989, and 1990 wheat crops were 65, 57, and 66%, respectively, for CT and 52, 52, and 53%, respectively, for NT, there being no significant ($P < 0\cdot05$) effect of tillage in any year or over all years.

At maturity, recovery of applied N (in grain and straw) for tillage treatments CT and NT was similar ($P > 0\cdot05$) for the 4 crops (data not presented). Thus, applied N recoveries in Table 2 are the means for the 2 tillage treatments. Applied N uptake in the year of fertiliser application ranged between 56 and 63%; recovery in the grain ranged between 39 and 49%. Uptake of applied N residues in the year following the application ranged between 2 and 7% (2–6% in grain), being equivalent to only 2–5 kg N/ha. Uptake of applied N residues by the third and fourth successive crops following N application were ~1% and <1% of that originally applied, respectively. Cumulative N recoveries in 4 successive wheat crops from the N applied in 1987 were 72% in the aboveground plant and 56% in the grain.

### *Available N (nitrate) supply to successive crops*

The quantity of N available (mostly $NO_3^-$-N since $NH_4^+$-N was negligible) for unfertilised wheat crops estimated just prior to sowing the crops each year ranged from 31 to 156 kg N/ha $\cdot$ 1 $\cdot$ 2 m (Table 3). In 1987, following a 19-month fallow due to a drought year in 1986, there was a significant ($P < 0 \cdot 05$) effect of tillage; more $NO_3^-$-N had accumulated in CT (156 kg/ha $\cdot$ 1 $\cdot$ 2 m) than in NT (105 kg/ha $\cdot$ 1 $\cdot$ 2 m), with the difference occurring mainly in the top 0 $\cdot$ 3 m (91 and 45 kg/ha for CT and NT, respectively). Available N supply to all other crops, following normal fallow periods of 6 or 7 months, was much lower (31–54 kg/ha $\cdot$ 1 $\cdot$ 2), there being no significant tillage effect.

**Table 2. Proportions (%) of applied $^{15}$N recovered in the year of application and by subsequent crops in a sequence of 4 wheat crops over 1987–90 on a Vertisol at Warra**

Values are means of conventional tillage and no till treatments for $^{15}$N recovered in grain and straw; values in parentheses are recoveries in grain

| Year of wheat crop | Year fertiliser applied[A] 1987 | 1988 | 1989 | 1990 |
|---|---|---|---|---|
| 1987 | 62·5 (45·7) | | | |
| 1988 | 7·2 (6·0) | 56·4 (44·8) | | |
| 1989 | 1·4 (1·2) | 2·4 (2·0) | 63·4 (48·9) | |
| 1990 | 0·8 (0·6) | 1·3 (1·1) | 3·6 (2·7) | 59·0 (38·8) |

[A] Fertiliser N depleted in $^{15}$N was applied at the rate of 75 kg/ha to each wheat crop where N had not been previously applied.

**Table 3. Antecedent mineral N supply (kg/ha $\cdot$ 1 $\cdot$ 2 m) for an unfertilised Vertisol to successive wheat crops over 1987–90 for 2 tillage treatments, conventional tillage (CT) and no till (NT), at Warra**

Tillage treatments marked with an asterisk are significantly ($P < 0 \cdot 05$) different

| Time of sampling[A] | Tillage treatment | $NO_3^-$-N to depth: 0·3 m | 1·2 m |
|---|---|---|---|
| May 1987 | CT | 91* | 156* |
| | NT | 45* | 105* |
| May 1988 | CT | 15 | 54 |
| | NT | 17 | 45 |
| May 1989 | CT | 12 | 44 |
| | NT | 19 | 49 |
| May 1990 | CT | 12 | 31 |
| | NT | 17 | 44 |

[A] Soil was sampled prior to wheat sowing.

Residual $NO_3^-$-N supply prior to wheat sowings in 1988, 1989, and 1990, after fertiliser N (75 kg/ha) had been applied to the previous crop, ranged from 32 to 97 kg/ha $\cdot$ 1 $\cdot$ 2 m (Table 4). On both tillage treatments, application of fertiliser N to the preceding crop increased the quantity of residual $NO_3^-$-N for the 1988 wheat crop but not for the 1989 or 1990 crop. Residual $NO_3^-$-N carried over to the 1988 crop was not evident in the top 0 $\cdot$ 3 m. More residual $NO_3^-$-N was available following the fertiliser application on CT (97 kg/ha $\cdot$ 1 $\cdot$ 2 m) than on NT (68 kg/ha $\cdot$ 1 $\cdot$ 2 m).

*Estimates of soil-available N pool from uptake of fertiliser and soil N*

The soil-available N pool (kg/ha) for wheat was estimated for each crop. For these estimates it was assumed that the proportional uptake of N originating from the soil and from fertiliser N applied at sowing would be similar. Thus, the available soil N pool was estimated from soil N uptake assuming that the same fraction was recovered as for fertiliser N. Values in Table 5 represent estimates of the soil-available pool for each of the 4 crops on the 2 tillage systems. Estimated pools for each tillage system were largest for the 1987 crop and were smallest for the 1989 and 1990 crops. Estimates for 1988 were intermediate in size with an ~30% larger pool for CT (130 kg N/ha) than for NT (98 kg N/ha). The estimates for 1988 reflect a similar proportional difference between tillage treatments as that for residual soil mineral-N levels determined to a depth of 1·2 m for CT (97 kg N/ha) and NT (68 kg N/ha).

**Table 4. Mineral N supply (kg/ha) to the wheat crops following N-fertilised wheat for 2 tillage treatments, conventional tillage (CT) and no till (NT), on a Vertisol at Warra**

Values are for soil that received 75 kg N/ha to preceding crop; those marked with an asterisk contain significantly ($P < 0\cdot05$) more $NO_3^-$-N than in unfertilised soil (values shown in parentheses)

| Time of sampling[A] | Tillage treatment | $NO_3^-$-N to depth: 0·3 m | 1·2 m |
|---|---|---|---|
| May 1988[B] | CT | 23 | 97*(54) |
| | NT | 19 | 68*(45) |
| May 1989 | CT | 10 | 53(44) |
| | NT | 14 | 52(49) |
| May 1990 | CT | 11 | 32(31) |
| | NT | 16 | 51(44) |

[A] Soil was sampled prior to sowing crop following N-fertilised wheat.
[B] Values for 1988 are for adjacent field plots; management was identical in every respect to that for this experiment.

**Table 5. Estimated pool of soil N (kg N/ha) available to 4 successive wheat crops, 1987–90, for 2 tillage treatments, conventional tillage (CT) and no till (NT), at Warra**

Nil N fertiliser was applied to preceding crops

Calculated from uptake of soil N into grain and straw assuming the same proportional recovery from soil as from the application of $^{15}$N-depleted ammonium nitrate applied annually at 75 kg N/ha: Estimated available soil N = $[(N_G+N_S)-(F_G+F_S)]/[(F_G+F_S)/F_N]$, where $N_G$ and $N_S$ are total N contained in grain and straw, respectively, $F_G$ and $F_S$ are quantities of the fertiliser N contained in grain and straw, and $F_N$ is the quantity of fertiliser N applied

| Tillage treatment | 1987 | 1988 | 1989 | 1990 |
|---|---|---|---|---|
| CT | 163 | 130 | 67 | 80 |
| NT | 144 | 98 | 78 | 94 |

## Discussion

Approximately 90% of the applied N recovered by the 4-crop sequence was taken up in the year of fertiliser application. A similarly high recovery of applied N in the year of application has been found with successive cropping in humid or temperate climates (Chichester and Smith 1978; Olson and Swallow 1979; Fredrickson *et al.* 1982; Kitur *et al.* 1984; Timmons and Cruse 1990; Walters and Malzer 1990; Chapman *et al.* 1992; Timmons and Baker 1992). In these more arid regions of subtropical Australia, applied N recovered by fertilised winter cereal crops should usually be at least as high as indicated by this sequence of crops.

After harvest of the fertilised crops, approximately 40% of the applied N was unaccounted for in aboveground plant parts. Averaged over the 4 crops and 2 tillage treatments (CT and NT), the proportions of applied N recovered in order of cropping sequence were $60 \cdot 3 \pm 4 \cdot 2$, $4 \cdot 4 \pm 2 \cdot 3$, $1 \cdot 3 \pm 0 \cdot 49$, and $0 \cdot 8 \pm 0 \cdot 56$%. The quantity of applied N which remained in the soil after crop harvest was not determined. However, $23 \cdot 15 \pm 6 \cdot 82$% of a $7 \cdot 5$ g N/m$^2$ application of $^{15}$N-enriched fertiliser was recovered in the soil ($0 \cdot 3$ m) on an adjacent site when averaged over the 4 years and 2 tillage treatments. Loss of applied N from the soil due to denitrification is presumed to constitute the remaining 17% of applied N not accounted for either in the aboveground plant parts or as estimated to be retained in the soil. Loss of applied N from Vertisols of the region was larger than this (32–43%) when N fertiliser was applied 1–3 months before sowing as is more usual (Strong and Cooper 1992) than when applied at sowing in these experiments.

Residual value of applied N from one crop to the next may be higher than determined in these experiments if higher rates of N are applied or if extreme drought periods prevent uptake of applied N. A large proportion (52–66%) of N applied in 1988, 1989, and 1990 was recovered in aboveground plant parts by the time of flowering. On similar soils, less applied N (32–42%) was recovered by wheat when drought occurred early during crop growth (Timmons and Baker 1992). During periods of drought, very little applied N may be taken up by wheat from dry topsoil (Armstrong *et al.* 1996). Following these extreme events, the carryover of fertiliser N to the next crop can be quite substantial (Strong *et al.* 1986).

Carryover benefits of fertiliser N applied in 1987 were due largely to soil-derived N, spared within subsoil layers below $0 \cdot 3$ m. In addition to the estimated applied N retained in the soil after harvest of the first crop ($17 \cdot 4 \pm 5 \cdot 1$ kg/ha), additional applied N ($8 \cdot 6$–$17 \cdot 2$ kg/ha) was returned with wheat residues. These sources of applied N combined provided only a very small N supply for subsequent wheat crops, $<5 \cdot 4$ kg/ha.

Because the source of N carryover was of soil origin, it is not surprising that the only measurable carryover effects during the 4-year cropping sequence occurred following fertiliser application in 1987. Large accumulation of soil $NO_3^-$-N in May 1987 (156 and 105 kg/ha$\cdot 1 \cdot 2$ m for CT and NT, respectively) was due to the influence of a long preceding period (19 months) of fallow. Apparently some of the large pool of available N remained unused in the fertilised soil by the 1987 crop and was carried over for use by the 1988 crop.

Such carryover effects of fertiliser N are reassuring in a climate of unreliable rainfall and thus variable crop response to supplementary N. Application of a moderate rate of applied N (e.g. 75 kg/ha) would appear to be a satisfactory routine practice to supplement N supplies for winter cereals in N-depleted soils of subtropical Australia. In spite of extreme variation in crop response to fertiliser, relatively safe preservation of $NO_3^-$-N in subsoil from one crop to the next may provide a suitable buffer for declining supplies of soil N in seasons of good crop response.

Heavier applications of N than that required to supplement depleted-N supplies for cereal crops are disadvantageous in this region for 2 reasons. They can reduce grain yields and/or profits in dry seasons (Strong *et al.* 1996). Furthermore, they may promote leakage of $NO_3^-$-N into subsoil layers and even beyond crop reach, as has been observed in this region (Dalal 1989) and in other arid regions (Campbell and Paul 1978). On adjacent and identically managed field plots, N applied at 150 kg/ha in 1988, 1989, or 1990 displaced 38 kg/ha more $NO_3^-$-N below 0·3 m before May, prior to sowing the next wheat crop. Applications of 75 kg N/ha did not increase $NO_3^-$-N displacement below 0·3 m.

## Conclusions

The large proportional (~60%) uptake of applied N by successive wheat crops between 1987 and 1990 suggests that only modest rainfall during winter, 63 mm in 1987 and 66 mm in 1990, was sufficient to enable good wheat recovery of N applied to a vertisol at sowing.

In spite of low recoveries of applied N by subsequent wheat crops (~6·5% of that applied), there may be considerable carryover benefit from fertiliser applied to the preceding crop. Additional N carried over in fertilised soil appeared to be soil-derived N, spared within subsoil layers below 0·3 m.

Residual effects of fertiliser N applications may not always be evident in this region of variable crop response to applied N, due to high incidence of water deficits for dryland crops. Residual effects of N fertiliser applications will be revealed only if the crop or crops which follow are not affected by water deficit, thus enabling uptake of available N from the soil profile. Also, carryover benefits should be particularly noticeable where fertiliser N is applied to crops with already moderate or high soil mineral N supplies.

## Acknowledgment

The authors express their appreciation to Incitec Ltd (formerly Consolidated Fertilisers Ltd) for the financial support for this research.

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Manuscript received 24 November 1995, accepted 15 February 1996