Plant and Soil **135**: 43–52, 1991.

PLSO 8677

The effects of nitrate: ammonium ratios and dicyandiamide on the nitrogen response of *Zea mays* L. in a high rainfall area on an acid soil

F.G. ADRIAANSE and J.J. HUMAN
Grain Crops Research Institute, Private Bag X1251, Potchefstroom 2520, Republic of South Africa and Department of Agronomy and Horticulture, University of the Orange Free State, Bloemfontein 9300, Republic of South Africa

Received 26 March 1990. Revised December 1990

Key words: DCD, field maize, N source

Abstract

Hydroponic studies under controlled environmental conditions indicated that maize plants respond better to combinations of nitrate and ammonium nutrition than to either form supplied separately but that this response depended upon the total N concentration. An attempt was made to maintain different nitrate: ammonium ratios and concentrations in the soil by the addition of a nitrification inhibitor. Five nitrate: ammonium ratios at three N application rates were tested with and without dicyandiamide ($H_2NC(NH)NHCN$) on a low-pH, sandy soil for two years. Treatments were applied to field-grown maize in two applications, one at planting and the other at 21 to 30 days after planting. Under favourable climatic conditions for crop growth the optimum nitrate: ammonium ratio for grain yield was between 3:1 and 1:1 over all N rates. Under unfavourable climatic conditions, ratios of 3:1 and 1:1 showed in contrast to all other ratios no grain yield depressions at high N rates. Dicyandiamide did not interact with N rates or ratios, but did increase grain yield over all N treatments under favourable conditions. N ratio interactions with N rates and dicyandiamide were also shown for N concentrations of the leaves at anthesis, for the grain at harvest and for mineral N in different soil layers at anthesis. These results imply that nitrate: ammonium ratios between 3:1 and 1:1 should be recommended at the optimum N rate on a low-pH sandy soil in a high rainfall area for maize production.

Introduction

Several research reports on numerous species, including maize, indicate that combinations of nitrate (NO_3) and ammonium (NH_4) result in better plant growth than either form supplied separately (Below and Gentry, 1987; Hageman, 1980, 1984; Hiatt, 1978; Shaviv and Hagin, 1988). Ammonium tolerance limits were, in contrast to that of nitrate, narrow with distinct yield optima followed by yield reductions as the NH_4 supply was increased and for this reason there is a need for careful control of NH_4^+ intake rates (Reisenauer, 1978). The optimum NO_3–N: NH_4–N ratio and N concentration for growing maize to maturity was shown to be close to 3:1 at 100 mg N L^{-1} while ammonium toxicity effects occurred from concentrations as low as 40 mg N L^{-1} at 200 mg N L^{-1} in a greenhouse-sand-hydroponic system (Adriaanse and Human, 1986, 1988 a, b).

Nitrification inhibitors have been identified which will slow the conversion of NH_4^+–N to NO_3^-–N by *Nitrosomonas*. Although the main objective with these chemicals was to minimize NO_3^-–N losses through denitrification and leaching, they may also be used to control the NO_3–N: NH_4–N ratio for the plant under field conditions. Research in the past was primarilly focused on nitrapyrin (Hoeft, 1984; Sahrawat and

Keeney, 1984). Dicyandiamide (DCD) has recently been firmly established as an effective nitrification inhibitor (Germann-Bauer and Amberger, 1989; Vilsmeier et al., 1987; Yadvinder-Singh and Beauchamp, 1989) which has advantages over nitrapyrin by being non-toxic, non-hygroscopic, and non-volatile and therefore considered more suitable for combination with solid fertilizers (German-Bauer and Amberger, 1989).

The optimum NO_3–N: NH_4–N ratio over two N rates, applied as nutrient solutions for field maize on a sandy soil was shown to be close to 3:1 without nitrapyrin and close to 1:3 with nitrapyrin in a low-potential grain yield area (Adriaanse and Human, 1990). The similar maize grain yield responses to $CO(NH_2)_2$ and NH_4NO_3, which were both better than to KNO_3 (Jung et al., 1972) would probably have been different if a nitrification inhibitor had been added. Toxic effects of NH_4 may occur by applying NH_4 as the principal source of N together with nitrapyrin under field conditions (Adriaanse and Human, 1990; Blackmer and Sanchez, 1988).

The objective of this research was to establish whether five NO_3–N: NH_4–N supply ratios with or without DCD, at three different N rates would result in different grain yield, leaf N and grain N responses for field maize on a sandy soil in a high-potential grain yield area.

Materials and methods

This study was conducted near Dundee, South Africa (28°10'S latitude, 30°18'E longitude, 1247 m elevation) on a sandy soil classified as a Avalon form, Avalon series (Macvicar et al., 1977). Soil analysis data before planting of the first trial are presented in Table 1. P and K were determined by a modified ISFI method described by Van der Merwe et al. (1984) and pH by using a soil-to-1 *M* KCl ratio of 1:2.5 according to Jackson (1958). Although extractable P concentrations were adequate for this soil (Table 1), 30 kg P ha^{-1} as superphosphate were broadcasted prior to planting of the first trial. K concentrations were inadequate (Table 1) and therefore 40 kg K ha^{-1} as KCl were broadcasted, together with half of the total N prior to planting of both trials. A disc-plough was used to incorporate these applications. Soil pH values were low (Table 1), but an acid saturation percentage of 22 for the 0–0.15 m zone indicated that soil acidity would not have restricted plant growth. The second half of the total N was broadcasted and incorporated into the soil by means of a tooth chisel at 30 and 21 days after planting for the first and second year, respectively.

A 5 × 3 × 2 factorial plus 2 controls consisting of the following 32 treatments were laid out in a randomized block design with three replications:

a. NO_3–N:NH_4–N ratios :1:0, 3:1, 1:1, 1:3 and 0:1 (R1 to R5, respectively).
b. N rates: 60, 120 and 180 kg N ha^{-1}.
c. Nitrification inhibitor: Dicyandiamide (DCD) was applied as 10% of the N rate to the above 15 treatments. Another set of these same 15 treatments received 10% of the N rate as urea in an attempt to balance the urea and NH_4 that is derived from the decomposition of DCD.
d. Controls: 1) 0 kg N ha^{-1} and no DCD.
    2) 220 kg N ha^{-1} at a 3:1 NO_3–N:NH_4–N ratio with DCD to check whether 180 kg N ha^{-1} at the same ratio was adequate for maximum grain yield.

The nitrogen carriers were calcium nitrate and ammonium sulfate. All N treatments were thoroughly mixed prior to application. Plot dimensions were 5.5 m × 3.6 m (4 rows) of which the middle 4.5 × 1.8 (2 rows) were harvested.

Table 1. Soil anlyses before planting

Soil layers	Extractable P ($mg\ kg^{-1}$)	Extractable K ($mg\ kg^{-1}$)	Clay ($g\ kg^{-1}$)	pH (KCl)
0–0.15 m	74.3	45.8	94	3.94
0.15–0.3 m	33.7	50.0	114	4.07
0.3–0.45 m	6.4	62.0	204	4.06

Table 2. Monthly precipitation (in mm) for the two seasons

Year	Aug	Sept	Oct	Nov	Dec	Jan	Feb	March	April	Total
1986/87	6.4	18.0	61.7	47.8	180.7	108.8	97.9	100.2	29.7	651.1
1987/88	65.0	190.1	58.9	112.0	75.0	133.8	114.9	105.5	51.0	906.2

The commercial prolific maize hybrid PNR473 was planted to effective plant densities of 41500 and 38700 plants ha^{-1} on 4th November 1986 and 17th November 1987, respectively. Pesticides were applied according to standard commercial practice for control of weeds and insects.

Soil and ear leaf samples were taken at anthesis on 21st January the first year and on 2nd February 1988 the second year. Soil samples for both trials were taken between the rows and for the first three 0.15-m soil depth increments. Each sample was composed by a thorough mix of three cores per plot. Soil samples were sun-dried and mineral N extracted by leaching 20 g of soil with 200 ml 1 *M* KCl. After this NO_3–N and NH_4–N were determined by steam distillation (Bremner, 1965). Leaf samples were taken from five plants per plot, one leaf per plant, immediately below the top ears. These samples were oven-dried at 70°C and analyzed for N content by Kjeldahl digestion (Jackson, 1958) using a semi microsystem, followed by auto-analyzer procedure based on a colorimetric method (Technicon Auto-Analyzer II, 1977).

Harvest dates were 12th May 1987 and 24th May 1988, and are referred to as the 1987 and 1988 trials, respectively, in the discussion. Ten cobs per plant were used to determine the shelling percentage. A 100-g grain sample from these cobs was used to determine the moisture percentage. Grain yield was corrected to 12.5% moisture. The same 100 g was oven-dried at 70°C for 48 hours and analyzed for N content by the same method as for the leaves.

The data were first analysed just for treatments and replications. After this the t-test was used to test the following contrasts (Cochran and Cox, 1964; Wonnacott and Wonnacott, 1972): (1) N rates positive linear, (2) N rates positive quadratic, (3) NO_3–N:NH_4–N ratios positive linear, (4) NO_3–N:NH_4–N ratios positive quadratic, (5) DCD better than no DCD, (6) N applications better than no N applications, (7) 220 kg N ha^{-1} better than 180 kg N ha^{-1} at a 3:1 ratio with DCD, 1 × 3, 1 × 4, 1 × 5, 2 × 3, 2 × 4, 2 × 5, 3 × 5, 4 × 5.

Ratios were tested for an increase in NH_4–N and a decrease in NO_3–N according to the order of application (R1 to R5).

The monthly precipitation is presented in Table 2.

Results and discussion

Grain yield

A comparison between all treatments which received nitrogen and the control plots which received no nitrogen showed that N applications did not generally increase grain yield in 1987. This was in direct contrast to the 1988 results (Table 3a, contrast 6). Grain yield responses to N applications were indicative of poor climatic

Table 3a. Levels of significance for the contrasts of interest tested for various plant characteristics (sign of contrast value in brackets)

Contrast	Grain yield		Leaf-N		Grain-N	
	1987	1988	1987	1988	1987	1988
1	0.09(−)	0.00(+)	0.59(+)	0.00(+)	0.06(+)	0.18(+)
2	0.03(+)	0.01(+)	0.89(+)	0.63(+)	0.38(−)	0.62(−)
3	0.53(+)	0.74(+)	0.47(+)	0.86(−)	0.59(+)	0.31(−)
4	0.53(−)	0.01(+)	0.42(−)	0.37(+)	0.58(−)	0.25(−)
5	0.62(−)	0.05(+)	0.26(−)	0.84(−)	0.22(−)	0.79(+)
6	0.49(+)	0.00(+)	0.89(+)	0.02(+)	0.02(+)	0.09(+)
7	0.93(−)	0.07(−)	0.81(−)	0.47(−)	0.50(+)	0.27(+)

Table 3b. Levels of significance for the contrast of interest tested for mineral N in the soil, 49 days after topdressing (sign of contrast value in brackets)

Contrast	NO_3-N						NH_4-N					
	1987			1988			1987			1988		
	0–0.15 m	0.15–0.3 m	0.3–0.45 m	0–0.15 m	0.15–0.3 m	0.3–0.45 m	0–0.15 m	0.15–0.3 m	0.3–0.45 m	0–0.15 m	0.15–0.3 m	0.3–0.45 m
1	0.00(+)	0.00(+)	0.00(+)	0.00(+)	0.00(+)	0.00(+)	0.00(+)	0.01(+)	0.06(+)	0.00(+)	0.00(+)	0.00(+)
2	0.43(−)	0.51(+)	0.07(+)	0.19(−)	0.01(−)	0.29(−)	0.33(−)	0.30(−)	0.72(−)	0.00(−)	0.49(+)	0.86(−)
3	0.00(−)	0.00(−)	0.58(−)	0.21(−)	0.01(−)	0.08(−)	0.00(+)	0.01(+)	0.00(+)	0.00(+)	0.79(−)	0.05(+)
4	0.06(−)	0.21(−)	0.92(+)	0.89(−)	0.15(−)	0.36(−)	0.00(−)	0.91(+)	0.04(−)	0.54(−)	0.09(+)	0.82(+)
5	0.07(−)	0.33(−)	0.92(−)	0.64(−)	0.39(−)	0.87(−)	0.73(+)	0.75(+)	0.34(−)	0.24(−)	0.19(+)	0.15(+)
6	0.07(+)	0.09(+)	0.03(+)	0.37(+)	0.25(+)	0.50(+)	0.04(+)	0.47(+)	0.03(+)	0.14(+)	0.58(−)	0.06(+)
7	0.00(+)	0.00(+)	0.76(+)	0.02(+)	0.00(+)	0.67(+)	0.08(+)	0.59(−)	0.74(+)	0.00(+)	0.61(+)	0.81(−)

conditions in 1987 and favourable conditions in 1988 (Table 4). Rainfall was both more plentiful and better distributed in 1988 than in 1987 (Table 2).

The interaction between N rate and NO_3-N:NH_4-N ratio was significant for yield in 1987 ($p = 0.04$). Grain yields were depressed by increases in the N rate from 120 to 180 kg N ha^{-1} at NO_3-N:NH_4-N ratios of 1:0 and 1:3 and from 60 to 180 kg N ha^{-1} at a ratio of 0:1 in this season (Table 4). A N rate of 180 kg N ha^{-1} did not, however, result in similar yield depressions at NO_3-N:NH_4-N ratios of 3:1 and 1:1 (Table 4). Even 220 kg N ha^{-1} at a ratio of 3:1 did not depress yield (Table 3a, contrast 7; Table 4). Increases in N rates did, however, not result in grain yield increases that were significant and therefore the application of N in excess of 60 kg ha^{-1} could not be justified under the 1987 conditions (Table 4). Furthermore, all ratios at 60 kg N ha^{-1} were statistically equivalent to each other (Table 4).

The interaction between N rate and NO_3-N:NH_4-N ratio was significant in 1988 ($p = 0.07$). There was a trend towards an optimum NO_3-N:NH_4-N ratio of 1:3 at 60 kg N ha^{-1} and 1:1 at 120 kg N ha^{-1} (Table 4). Significantly more grain was produced at 120 kg N ha^{-1} than at 60 kg N ha^{-1} for all NO_3-N:NH_4-N ratios except the 1:3 ratio (Table 4). All ratios indicated a trend towards optimum grain yield production at N rates close to 120 kg N ha^{-1}, since the differences between 120 and 180 kg N ha^{-1} were in no instance significant (Table 4). A significant yield depression resulted from an increase in the N rate from 180 to 220 kg N ha^{-1} at a NO_3-N:NH_4-N ratio of 3:1 (Table 3a, contrast 7; Table 4). Many NO_3-N:NH_4-N ratios were statistically equivalent at 120 kg N ha^{-1} and only 1:1 was superior to 0:1 (Table 4). On the other hand, only ratios of 1:1 and 3:1 at 120 kg N ha^{-1} were superior to a ratio of 1:3 at 60 kg N ha^{-1} (Table 4). From these results it therefore appeared as if the optimum NO_3-N:NH_4-N ratio was between 3:1 and 1:1 at 120 kg N ha^{-1}. A focus on the highly significant main effects of ratios and N rates resulted to very much the same conclusions. Over all N rates the optimum NO_3-N:NH_4-N ratio also appeared to be between 3:1 and 1:1 (Table 3a, contrast 4; Table

Table 4. Grain yield (kg ha^{-1}) for NO_3–N: NH_4–N ratios and N rates averaged over treatments with and without dicyandiamide

NO_3–N : NH_4–N (ratios)	1987				1988			
	N rate (kg N ha^{-1})				N rate (kg N ha^{-1})			
	60	120	180	av.	60	120	180	av.
1 : 0	5075	5513	4280	4956	6793	8343	8820	7985
3 : 1	4703	4730	4795	4742	7735	9051	9213	8666
1 : 1	4795	4951	4983	4909	7683	9310	8750	8581
1 : 3	4802	5600	4493	4964	8005	8705	8877	8529
0 : 1	5499	5286	4394	5059	7153	8244	9090	8162
LSD (0.05)		1024		591		1015		586
N rate (av.)	4974	5216	4588		7474	8731	8950	
LSD (0.05)		458				454		
Controls:								
N = 0 kg N ha^{-1}		4563				4623		
N = 220 kg N ha^{-1} at a 3 : 1 ratio + DCD		4954				8362		
C.V.		18.0%				10.5%		

4). Similarly over all NO_3–N : NH_4–N ratios the optimum N rate appeared to be close to 120 kg N ha^{-1} (Table 3a, contrast 2; Table 4). Substantiation for an optimum NO_3–N : NH_4–N ratio close to 3 : 1 without a nitrification inhibitor over N rates on a similar soil type in a different climatic region was given by Adriaanse and Human (1990). A 3 : 1 ratio also corresponds to the results of Adriaanse and Human (1986, 1988 a, b) at 100 mg N L^{-1} in a greenhouse-sand-hydroponic system.

The application of DCD resulted in higher grain yields over all ratios and N rates in 1988 (8569 compared to 8201 kg ha^{-1}) but not in 1987 (Table 3a, contrast 5). Although DCD might have played a limited part in inhibiting the nitrification of applied and residual NH_4^+–N, nitrification was expected to be very slow with or without DCD in this strongly acid soil (Adams and Martin, 1984; Vilsmeier et al., 1987). The explanation for this result may be that DCD was a more effective N source than urea since its decomposition is slower than that of urea (Vilsmeier et al., 1987).

N concentration in the plant

The N concentrations in the leaves were higher with the application of nitrogen than without in 1988, but not in 1987 (Table 3a, contrast 6). Similarly, linear responses to N rates were evident in 1988 but not in 1987 (Table 3a, contrast 1; Table 5). The reason for this difference between years was probably that soil moisture was adequate to give a N uptake response in 1988 but not in 1987. Other research showed that N rate had no effect on N uptake when the seasonal rainfall was 600 mm, but that this effect was marked when 200 mm or more irrigation was added (Bennett et al., 1989).

Interactions between N rates and DCD for the N concentration in the leaves were only evident in 1988 ($p = 0.03$; Table 6). Concentrations increased according to increases in the application level from 120 to 180 kg N ha^{-1} with DCD and from 60 to 120 kg N ha^{-1} without DCD (Table 6). These differences in trends were apparently due to the interaction of different factors. As mentioned earlier, it was expected that DCD

Table 5. N concentration (g kg^{-1}) in the leaves at anthesis and in the grain at harvest for N rates averaged over NO_3–N : NH_4–N ratios and DCD

N rate (kg N ha^{-1})	N in leaves		N in grain	
	1987	1988	1987	1988
60	26.9	25.8	15.9	13.4
120	27.2	27.2	15.9	13.5
180	27.3	28.2	16.5	13.8
LSD (0.05)	2.2	1.0	0.6	0.5
Controls:				
N = 0 kg N ha^{-1}	27.0	24.3	14.3	12.5
N = 220 kg N ha^{-1} at a 3 : 1 ratio + DCD	26.7	27.1	16.6	14.5

Table 6. N concentration (g kg^{-1}) in the leaves at anthesis for N rates with and without DCD, averaged over NO_3-N:NH_4-N ratios for the 1988 season

N rate (kg N ha^{-1})	+DCD	−DCD
60	26.3	25.3
120	26.5	27.9
180	28.3	28.1

LSD (0.05) = 1.5.

Table 7. N concentration (g kg^{-1}) in the grain at harvest for NO_3-N:NH_4-N ratios with and without DCD averaged over N rates in 1987

Ratio NO_3-N:NH_4-N	+DCD	−DCD
1:0	16.1	16.1
3:1	15.5	16.5
1:1	15.3	16.2
1:3	16.1	16.7
0:1	16.6	15.7

LSD (0.05) = 1.2.

would increase NH_4-N uptake relative to NO_3-N over time. From a controlled nutrient medium it was shown that the leaf N concentration was increased with increasing NH_4^+-N ratios (Adriaanse and Human, 1986, 1988 b). Nitrate uptake was on the other hand favoured over ammonium uptake at this low soil pH (Blair et al., 1970).

Nitrogen concentration in the grain was higher with the application of nitrogen than without in 1987 and in 1988 ($p = 0.02$ and 0.09, respectively, Table 3a, contrast 6). The linear responses to N rates were significant in 1987 ($p = 0.06$), but not in 1988 (Table 1, contrast 1; Table 5). These N concentrations were much higher in 1987 than in 1988. Other researchers showed similar differences in the minimum N concentration in the grain at which maximum grain yield was obtained between years (Coffman, 1981). A negative association between grain yield and grain N concentration (Russell and Pierre, 1980) may explain the low grain N concentrations and lack of response to N rates in 1988. Weather conditions such as moisture stress, adverse temperatures and solar radiation may also affect the relative amount of carbohydrates and protein synthesized or translocated to the grain (Asghari and Hanson, 1984; Pierre et al., 1977). Interactions between DCD and NO_3-N:NH_4-N ratios were again only evident in 1987 ($p = 0.02$). There were, however, no significant differences between treatments with and without DCD at the same NO_3-N:NH_4-N ratio (Table 7).

Mineral nitrogen concentration in the soil

The concentrations of NO_3-N and NH_4-N at 49 days after top dressing varied linearly according to the levels and ratios of application, especially in the topsoil but also in the subsoil layers (Table 3b, contrast 1 and 3).

Interactions between NO_3-N:NH_4-N ratios and N rates for NO_3-N and NH_4-N are presented in Figure 1. The NH_4-N concentrations relative to the NO_3-N concentrations were generally much higher in the 0–0.15 m zone when compared to the ratios at which they were applied in 1987 as well as 1988 (Fig. 1). However, the NH_4-N concentrations relative to the NO_3-N concentrations were lower in the 0.15–0.3 m and 0.3–0.45 m zones in both seasons. From this it is evident that NH_4-N remained mostly in the topsoil while NO_3-N leached to the subsoil. Another possible reason for this result in the topsoil may be that there was preferential uptake of NO_3-N by the plant compared to NH_4-N at the low pH of 3.94 (Table 1) (Blair et al., 1970).

The concentrations of NO_3-N and NH_4-N were much higher in 1987 than in 1988 in all three soil zones (Fig. 1, Table 8). The apparent reasons were that the maize plants took up less nitrogen and that the losses of nitrogen were less during the drier season of 1987 compared to that of 1988 (Table 2).

A comparison between the mineral N in the 0 kg N ha^{-1} control plots (Table 8) to other N treatments in Table 8 and Fig 1 indicated substantial differences at high application rates. An increase in the N rate from 180 to 220 kg N ha^{-1} at a NO_3-N:NH_4-N ratio of 3:1 resulted in increases in NO_3^--N concentration in the 0–0.15 m and 0.15–0.30 m zones and in NH_4-N in the 0–0.15 m zone in both seasons (Table 3, contrast 7).

Interactions between DCD and N rates were shown for NO_3-N in the 0–0.15 m and 0.15–0.30 m zones but only in 1987. The application of

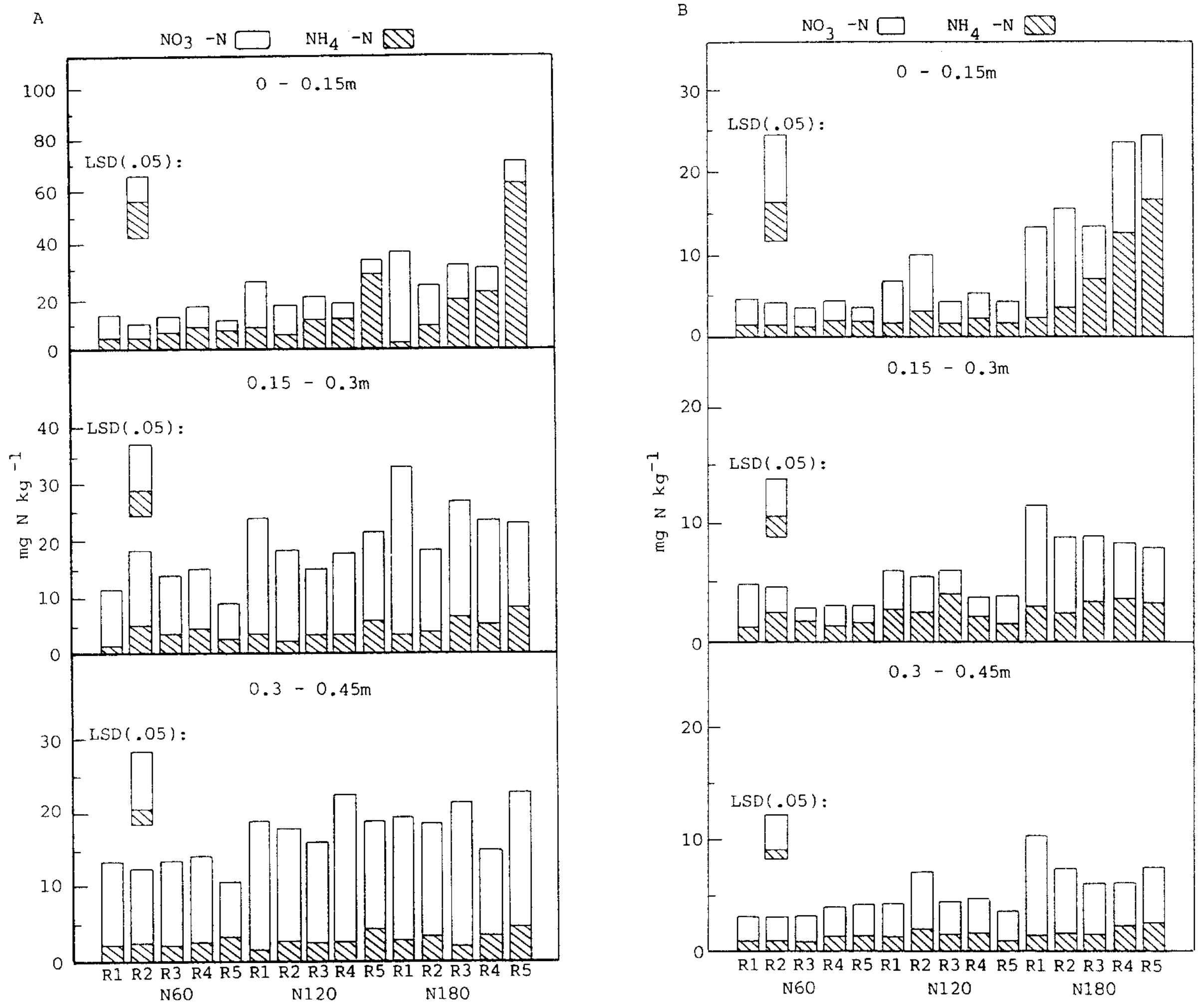

Fig. 1. Mineral N concentrations in three soil layers for varying nitrate: ammonium ratios, 49 days after topdressing, 77–78 days after planting for 1987 (**A**) and 1988 (**B**). Concentrations were averaged per N rate (60, 120 or 180 kg N ha^{-1}) over treatments with and without dicyandiamide. Application ratios of nitrate-N: ammonium-N were 1:0 (R1), 3:1 (R2), 1:1 (R3), 1:3 (R4) and 0:1 (R5).

Table 8. Soil mineral N (mg N kg^{-1}) and pH (KCl) for controls

Soil layer	1987						1988					
	0 kg N ha			220 kg N ha^{-1a}			0 kg N ha			220 kg N ha^{-1a}		
	NO_3-N	NH_4-N	pH	NO_3-N	NH_4^+-N	pH	NO_3-N	NH_4-N	pH	NO_3-N	NH_4-N	pH
0–0.15 m	1.9	0.3	3.94	38.1	25.1	3.98	1.7	0.4	4.14	27.1	16.3	4.03
0.15–0.3 m	8.3	2.8	4.07	29.7	2.4	3.95	1.6	2.8	4.29	13.8	2.8	4.27
0.3–0.45 m	5.4	0.8	4.06	16.5	2.6	3.89	2.6	0.6	4.01	5.3	2.0	3.94

[a] The NO_3-N:NH_4-N ratio was 3:1 and dicyandiamide was applied.

Table 9. The NO_3-N concentration in two soil zones, 49 days after top dressing, with and without DCD for 1987

N rates (kg N ha^{-1})	NO_3-N conc. (mg kg^{-1}) +DCD	−DCD	LSD (0.05)
	0–0.15 m		
60	6.49	7.11	6.57
120	11.34	9.73	
180	11.84	23.17	
	0.15–0.3 m		
60	11.34	10.01	5.55
120	17.31	16.32	
180	17.15	24.23	

DCD resulted in lower NO_3-N concentrations than without DCD in the 0–0.15 m and 0.15–0.30 m zones but only at 180 kg N ha^{-1} (Table 9). The apparent reason for this was that DCD was effective in slowing the nitrification of NH_4-N at 180 kg N ha^{-1}. Interactions between DCD and N rates for NH_4-N were shown in the 0–0.15 m zone, but only for 1988. There was, however, a lack of significant differences for NH_4-N concentrations between treatments with and without DCD at the same N rate (Table 10).

Interactions between DCD and NO_3-N:NH_4-N ratios were shown for NH_4-N but only in the 0.3–0.45 m zone and only in 1988. A NO_3-N:NH_4-N ratio of 1:3 was the only ratio at which the NH_4-N concentration was higher with than without DCD (Table 10). These NH_4-N concentrations were, however, very low and therefore this difference was not considered as being of particular importance.

Conclusions

Grain yield depressions due to high N rates were less likely to occur at NO_3-N:NH_4-N ratios of 3:1 and 1:1 than at 1:0, 1:3 and 0:1 when precipitation was limiting and the general response to N was poor. Under favourable climatic conditions the optimum NO_3-N:NH_4-N ratio for grain yield was also between 3:1 and 1:1 over all N rates.

DCD increased grain yield over all N treatments under favourable climatic conditions, but showed no interactions with NO_3-N:NH_4-N ratios in this regard, the apparent reason being that DCD played a significant part as a N source but not as a nitrification inhibitor in this acid soil.

N concentrations in the leaves were affected by N rates, but only under favourable climatic conditions for crop growth while this effect on the N concentrations in the grain was more pronounced under less favourable conditions.

Mineral N concentrations in the soil at anthesis were much higher under low precipitation and low grain yield response conditions than under high precipitation conditions.

NO_3-N concentration relative to NH_4-N concentration was low in the topsoil and high in the subsoil due to the combined soil and plant responses to variation in NO_3-N:NH_4-N ratios.

DCD showed some effect on NO_3-N and NH_4-N concentrations in the top and subsoil at anthesis, but the significance thereof was not altogether clear. DCD contributed to the main-

Table 10. The NH_4-N concentration in two soil zones, 49 days after top dressing with and without DCD for 1988

N rate (kg N ha^{-1})	NH_4-N conc. (mg kg^{-1}) +DCD	−DCD	LSD (0.05)
	0–0.15 m		
60	1.8	1.32	4.6
120	2.22	2.00	
180	6.64	10.47	
Ratio NO_3-N:NH_4-N			
	0.3–0.45 m		
1:0	1.18	1.18	0.69
3:1	1.46	1.50	
1:1	1.37	1.16	
1:3	2.42	0.97	
0:1	1.37	1.85	

tenance of applied NO_3–N : NH_4–N ratios in the 0.15–0.30 m zone at 180 kg N ha^{-1} by lowering the NO_3–N concentration in this zone. However, the effect of DCD to lower the NO_3–N concentration in the 0–0.15 m zone at 180 kg N ha^{-1} further distorted the applied NO_3–N : NH_4–N ratios towards lower NO_3–N concentrations relative to NH_4–N over time.

Difficulties that were experienced in maintaining NO_3–N : NH_4–N ratios, especially high NO_3–N ratios relative to NH_4–N in the topsoil led to the suggestion that the best way to optimize a NO_3–N : NH_4–N uptake ratio under field conditions would be a method of multiple N applications with most of the N being applied during the peak uptake period of the plant.

Acknowledgements

The authors thank the Department of Agricultural Development for financing this research, Dr B E Eisenburg and especially Mr P J van Rooyen for statistical analyses of contrasts, Mr D de V Bruwer and Mr W D Pieters for technical assistance and Mrs G van der May for laboratory analyses.

References

Adams F and Martin J B 1984 Liming effects on nitrogen use and efficiency. *In* Nitrogen in Crop Production. Ed. R D Hauck, pp 417–426. Amer. Soc. Agron. Madison, WI.

Adriaanse F G and Human J J 1986 The part played by nitrate: ammonium ratios in effective nitrogen utilization by *Zea mays* L. S. Afr. J. Plant Soil 3, 57–60.

Adriaanse F G and Human J J 1988a Effect of different nitrate: ammonium ratios on the development of *Zea mays* L. S. Afr. J. Plant Soil 5, 120–122.

Adriaanse F G and Human J J 1988b The relative importance of the form and concentration of nitrogen in the root zone on the development of *Zea mays* L. S. Afr. J. Plant Soil 5, 123–126.

Adriaanse F G and Human J J 1990 The effects of nitrate: ammonium ratios and nitrapyrin on the nitrogen response of *Zea mays* L. under field conditions. Plant and Soil 122, 287–293.

Asghari M and Hanson R G 1984 Nitrogen, climate and previous crop effect on corn yield and grain N. Agron. J. 76, 536–542.

Below F E and Gentry L E 1987 Effects of mixed N nutrition on nutrient accumulation, partitioning and productivity of corn. J. Fert. Issues 4, 79–85.

Bennett J M, Mutti L S M, Rao P S C and Jones J W 1989 Interactive effects of nitrogen and water stresses on biomass accumulation, nitrogen uptake, and seed yield of maize. Field Crops Res. 19, 297–311.

Blackmer A M and Sanchez C A 1988 Response of corn to nitrogen-15-labeled anhydrous ammonia with and without nitrapyrin in Iowa. Agron. J. 80, 95–102.

Blair G J, Miller M H and Mitchell W A 1970 Nitrate and ammonium as sources of nitrogen for corn. Agron. J. 62, 530–532.

Bremner J M 1965 Nitrogen availability indexes. *In* Methods of Soil Analysis. Ed. C A Black. Part 2. Agron. 9, pp 1191–1206. Amer. Soc. Agron. Madison, WI.

Cochran W G and Cox G M 1964 Experimental Designs. pp 61–76. Wiley, New York.

Coffman C G 1981 The critical nitrogen percentage in the grain of maize single crosses and their parental lines, and efficiency of nitrogen utilization by different single crosses. Ph.D. thesis, Iowa State University, Iowa.

Germann-Bauer M P and Amberger A 1989 Degradation of the nitrification inhibitor 1-amidino-2-thiourea in soils, and its action in Nitrosomonas pure culture and soil incubation experiments. Fert. Res. 19, 13–19.

Hageman R H 1980 Effect of form of nitrogen on plant growth. *In* Nitrification Inhibitors, Potentials and Limitations. Eds. J J Messinger et al. pp 47–62. ASA Spec. Pub. 38, Amer. Soc. Agron. Madison, WI.

Hageman R H 1984 Ammonium versus nitrate nutrition of higher plants. *In* Nitrogen in Crop Production. Ed. R D Hauck. pp 67–85. Amer. Soc. Agron. Madison. WI.

Hiatt A J 1978 Critique of 'Absorption and utilization of ammonium nitrogen by plants' *In* Nitrogen in the Environment, Vol. 11: Soil-plant-nitrogen Relationships. Eds. D R Nielsen and J G MacDonald. pp 191–199. Academic Press, New York.

Hoeft R G 1984 Current status of nitrification inhibitor use in U.S. agriculture. *In* Nitrogen in Crop Production. Ed. R D Hauck. pp 561–570. Amer. Soc. Agron. Madison, WI.

Jackson M L 1958 Soil Chemical Analysis. Constable and Company, London.

Jung P E, Peterson A and Shrader L E 1972 Response of irrigated corn to time, rate and source of applied N on sandy soils. Agron. J. 64, 668–670.

Macvicar C N, de Villiers J M, Loxton R F, Verster E, Lambrechts J J N, Merryweather F R, Le Roux J, van Rooyen T H, and Harmse H J von M 1977 Soil classification: A binomial system for South Africa. Dept. Agric. Tech. Serv. Sic. Bull. 390, Pretoria.

Pierre W H, Dumenil L, Jolley V D, Webb J R and Shrader W D 1977 Relationship between corn yield expressed as a percentage of maximum and the N percentage in the grain. I. Various N-rate experiments. Agron. J. 69, 215–220.

Reisenauer H M 1978 Absorption and utilization of ammonium nitrogen by plants. *In* Nitrogen in the Environment, Vol. II: Soil-plant-nitrogen. Relationships. Eds. D R Nielsen and J G MacDonald. pp 157–189. Academic Press, New York.

Russell W A and Pierre W H 1980 Relationship between maize single crosses and their parent inbred lines for N content in the grain. Agron J. 72, 363–369.

Sahrawat K L and Keeney D R 1984 Effects of nitrification inhibitors on chemical composition of plants: A review. J. Plant Nutr. 7, 1251–1288.

Shaviv A and Hagin J 1988 Interaction of ammonium and nitrate nutrition with potassium in wheat. Fert. Res. 17, 137–146.

Technicon Auto-analyzer II 1977 Individual/simultaneous determination of nitrogen and/or phosphorus in BD acid digests. Industrial Method No. 334-74W/B$^+$. Technicon Industrial Systems/Tarrytown, New York.

Van der Merwe A J Jonson J C Ras LSK 1984 A NH_4HCO_3-NH_4F-$(NH_4)_2$-EDTA-method for the determination of extractable P, K, Ca, Mg, Cu, Fe, Mn and Zn in soils. Information Bulletin B2/2, Soil Irrigation Res. Inst., Pretoria.

Vilsmeier K, Bornemisza E and Amberger A 1987 Urea, ammonium sulfate and dicyandiamide transformations in Costa Rican soils. Fert. Res. 12, 255–261.

Wonnacott J H and Wonnacott R J 1972 Introductory Statistics. pp 189–195. Wiley, New York.

Yadvinder-Singh and Beauchamp E G 1989 Nitrogen transformations near urea in soil: effects of nitrification inhibition, nitrifier activity and liming. Fert. Res. 18, 201–212.