Journal of Agricultural Science, Cambridge (1997), **128**, 263–271. © 1997 *Cambridge University Press*

Urea as a nitrogen fertilizer for cereals

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(*Revised MS received 15 August 1996*)

SUMMARY

Twenty-six experiments were carried out in England and Wales from 1983 to 1985 to compare urea and ammonium nitrate (AN) as N top-dressing for cereals over the range 100–300 kg/ha N. Most of the experiments were sited on chalky or other soils of pH > 7·0 where the greatest differences in effectiveness were expected.

The results showed that while relative N offtake in grain was 2·5% greater from AN, there was no difference in grain yield. Splitting the main N application increased N offtake from urea but not from AN. Overall, urea effectiveness from a single application at GS 31 increased with increasing rainfall on the day of application, but was not increased by subsequent rainfall. On chalk soils, urea effectiveness increased with increasing cumulative rainfall up to the fifth day after application. There was little effect of rainfall on urea effectiveness when the dressing was split. Although grain yield was unaffected by the type of fertilizer N applied, grain N concentration was usually less from urea.

The fertilizer N requirement for optimum yield (N_{opt}) was similar for both fertilizers. Splitting the main N application had no effect on yield or N_{opt}. We conclude that urea is a satisfactory source of N for cereals.

INTRODUCTION

Since the early 1950s, urea has been the world's main source of fertilizer N. However, in the UK, the great majority of fertilizer N has been applied as ammonium nitrate (AN). Gasser (1964) reviewed the use of urea as a source of fertilizer N, concluding it was somewhat inferior to AN, because it either damaged germinating seeds and young plants (e.g. cereals and sugarbeet), or lost ammonia to the atmosphere after application. Field experiments in the UK showing that urea may be less effective than other nitrogen fertilizers (e.g. Devine & Holmes 1963) have limited its use in the UK; from 1990 to 1994 only *c*. 15–20% of N top-dressing to cereals was in the form of urea (e.g. Anon. 1994*a*).

In an earlier paper, Lloyd (1992) found average yields of first cut silage were 2% less from urea than from AN. Moreover, despite the greater cost of AN, there was little difference between the economic optimum application rates (N_{opt}) of the two fertilizers and hence no need to compensate for the lesser efficiency of urea by increasing the rate of application. Chaney & Paulson (1988) found urea to be an inferior N source when applied to arable crops. However, their comparisons included only one or two rates of N application and so the feasibility of using extra urea to compensate for its lesser efficiency could not be evaluated. No consistent differences in yield loss could be related to texture, pH or climate by Chaney & Paulson (1988) or Lloyd (1992). However O'Toole & Morgan (1988) found ammonia losses from urea to be most likely in soils with a low cation exchange capacity (CEC) under warm, dry conditions, and they measured greater ammonia losses from arable than from grassland soils. The general conclusion regarding the comparison of these two sources of N fertilizer for the top-dressing of winter cereals under UK conditions has always favoured AN, but often by only a small amount. Very few experimental comparisons have been carried out on winter cereals producing current yields (6·5 t/ha for winter wheat; 4·9 t/ha for winter barley).

This paper presents the results from experiments in England and Wales during 1983–85 in which AN and urea were applied to winter cereals. The objective was to investigate the comparative effectiveness of urea as a N source and to identify the soil and climatic factors that may influence its behaviour.

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Table 1. *Details of experimental sites in England and Wales 1983–85 to compare the effectiveness of urea and ammonium nitrate as sources of fertilizer nitrogen for cereals, winter wheat (ww) and winter barley (wb)*

							At depth of 0–15 cm		
Site	Year	Site name	County	Topsoil texture	Soil series	Cereal variety	pH	Organic matter (%)	$CaCO_3$ (%)
B1	1983	Easton	Hampshire	Silty loam	Andover	WW Hustler	8·2	5·1	2·6
B2	1983	Micheldever	Hampshire	Silty loam	Andover	WW Avalon	8 0	3·9	4·9
B4	1983	Sladesbridge	Cornwall	V.f. sandy loan	Denbigh	WW Rapier	7·5	6·5	4·0
B5	1983	Boscar Grange	N Yorkshire	Loamy fine sand	Everingham	WB Igri	7·1	1·3	0·0
B6	1983	High Mowthorpe	N Yorkshire	Silty clay loam	Andover	WW mixture	8·1	4·2	7·6
B7	1983	Cotswold CC	Gloucestershire	Silty clay loam	Evesham	WW Norman	7·3	4·6	5·0
B8	1983	Daltons	Dorset	Silt loam	Upton	WW Prince	8·0	4·9	57·0
B9	1983	Boxworth	Cambridgeshire	Clay loam	Hanslope	WW–	8·1	3·9	15·0
B10	1983	Low Caythorpe	Humberside	Silty clay loam	Coombe	WW Avalon	8·0	3·8	3·4
B11	1983	Foston	Humberside	Clay loam	Romney	WW Avalon	6·8	3·9	0·0
C1	1984	Aldwark	N Yorkshire	Loamy sand	Kexby	WB Igri	6·3	1·4	0·1
C2	1984	Thornton Hall	Durham	Clay loam	Brickfield	WB mixture	6·4	3·9	0·2
C3	1984	High Mowthorpe	N Yorkshire	Silt loam	Andover	WW Aquila	7·8	6·2	4·9
C4	1984	Bubwith	N Yorkshire	Sandy loam	Kexby	WW Brigand	6·9	1·4	0·0
C5	1984	Garton	Humberside	Silt loam	Andover	WW Longbow	8·1	4·1	10·6
C6	1984	Fordon	Humberside	Silt loam	Andover	WW Prince	7·6	4·9	1·3
C7	1984	Overton	Hampshire	Silty loam	Andover	WW Rapier	7·8	5·1	4·7
C8	1984	Red Rice	Hampshire	Silty loam	Andover	WW Rapier	7·5	3·3	12·9
C9	1984	Cotswold CC	Gloucestershire	Silty clay loam	Sherborne	WW Longbow	8·0	6·0	16·3
C10	1984	Daltons	Dorset	Silt loam	Upton	WW Avalon	7·9	6·6	30·6
C11	1984	Boxworth	Cambridgeshire	Clay loam	Hanslope	WW Longbow	8·3	2·9	11·5
C12	1984	Langston	Devon	V.f. sandy loam	Denbigh	WB Igri	6·4	4·6	0·1
C13	1984	Llanfaelog	Gwynedd	Sandy loam	East Keswick	WW Norman	6·4	5·1	0·0
D2	1985	Ashcombe	Devon	Clay loam	Credition	WB Panda	6·7	3·8	0·2
D3	1985	Egmere	Norfolk	Sandy loam	Barrow	WW Longbow	7·9	1·1	0·0
D4	1985	Cotswold CC*	Gloucestershire	Silty clay loam	Sherborne	WW Avalon	8·2	5·1	16·0

* CC, Cereal Centre.

MATERIALS AND METHODS

Twenty-six experiments were laid down on a range of soils, on commercial farms in the cereal-growing areas of England and Wales. The sites chosen were biased to include a number of chalk soil types, mainly Upton and Andover series, because it was anticipated that these would be more likely to show any yield disadvantage from urea compared with AN. The Andover series is a slightly stony, calcareous, silty clay loam to *c.* 20 cm depth, over fragmented chalk. The Upton series is a moderately stony, extremely calcareous, silty clay loam to *c.* 30 cm depth over fragmented chalk. Based on previous cropping, the N Index system used by ADAS (Anon. 1994*b*) placed most sites in N Index 0. This Index was chosen to ensure a substantial yield response to N fertilizer. There was one exception, site C9 (Table 1), which, having followed a 3-year temporary grass ley, was N Index 1. Winter wheat was the test crop at 21 sites and winter barley at five sites.

At each site, prilled AN (34·5% N) and prilled urea (46% N) were applied by hand at the following rates: 0, 100, 140, 180, 220, 260, 300 kg N/ha. At all sites, differences in timing of the two fertilizers were tested. Because it had become obvious that a small N dressing at early tillering (growth stage (GS) 21) generally gave a yield benefit on N Index 0 soils (Sylvester-Bradley *et al.* 1984), plots at all sites received 40 kg N/ha of their total spring N application in late February or early March. The remaining dressing was either applied all at GS 30/31 or split, with half at GS 30/31 and half *c.* 2 weeks later.

The experiment at each site was a three-way factorial plus duplicated nil N control, in a randomized block design with two replicates. The sites, even when in the same locality, were on different fields in successive years. They all had satisfactory soil pH values; in most the phosphorus (P) and potassium (K) contents from previous fertilizer management were sufficient: if not, lime and fertilizers were applied, prior to the start of the experiment, to ensure that neither pH nor PK deficiencies limited cereal growth. Herbicide, fungicide and pesticide applications were carried out by the farmers as required. Site details are given in Table 1.

A minimum area of 50 m^2 was harvested by combine harvester from each *c.* 70 m^2 plot and grain yields expressed at 85% dry matter. Grain N concentrations were measured by near infra-red spectroscopy (Anon. 1986) and expressed as a percentage N in the grain dry matter on a weight basis.

Statistical analysis

Comparisons between the two fertilizers, amounts of fertilizer N applied and timing of fertilizer N application, were made for each experiment by analysis of variance. Similar comparisons were also made using the whole data set to determine if any of the effects differed from site to site. An orthogonal contrast was included in the cross-site analysis to identify any differences between chalk and non-chalk sites.

Two straight lines were fitted to grain N offtake (N$_{\text{off}}$) data, following the method of Bloom *et al.* (1988). The function was of the form:

$$\mathrm{N}_{\text{off}} = [N < t \times \{a - b(t - N)\} + N > t \times \{a + c(N - t)\}]$$

Where N is grain N and a, b, c and t are parameters estimated for each data set.

Apparent fertilizer recoveries (AFR) at the fertilizer N application for economic optimum yield (N$_{\text{opt}}$) were estimated for each experiment for both fertilizer types and for single and split timing, using the following formula:

$$\text{AFR at N}_{\text{opt}} = \frac{\text{N}_{\text{off}}\text{ at N}_{\text{opt}} - \text{N}_{\text{off}}\text{ at N}_{0}}{\text{N}_{\text{off}}\text{ at N}_{\text{opt}}}$$

For each experiment the model $Y = a + b(1 - r^x) + cX$ was used to describe the relationship between grain yield and level of applied N for each of the timing/fertilizer combinations within trials. This alternative parameterization of the standard linear plus exponential (LPE) model (George 1984) ensures that $Y = a$ (rather than $a + b$) at $X = 0$, making it simple to constrain the curves within an experiment to have single intercept. The parameter r was constrained at 0·99 to be common over all experiments, so that the final model fitted to the combined data was:

$$Y = a_i + b_{ijk}\,(1–0{\cdot}99^x) + c_{ijk}X$$

where i represents experiment ($i = 1 \dots 26$), j represents fertilizer type ($j = 2{,}3$), and k represents timing ($k = 2{,}3{,}$). The model thus contains a single r, 26 separate a parameters (one for each experiment) and four values of b and c for each experiment. The N$_{\text{opt}}$ for each fertilizer N source and timing combination at each site was chosen as the amount of N at which the rate of response reached 3 kg of grain per kg of N applied (Sylvester-Bradley *et al.* 1984).

The relative uptake of N from urea compared with AN was assessed as Urea Relative N offtake (URN$_{\text{off}}$) where

$$\text{URN}_{\text{off}} = \frac{\text{mean N}_{\text{off}}\text{ with urea}}{\text{mean N}_{\text{off}}\text{ with AN}} \times 100\,\%$$

Urea relative yield (URY) was similarly defined as

$$\text{URY} = \frac{\text{mean yield with urea}}{\text{mean yield with AN}} \times 100\,\%$$

Such estimates of URN$_{\text{off}}$ and URY derived would cover any range of N optima caused by fluctuations in the price of grain or fertilizer.

Other relationships between data were also assessed by straight-line regression using MINITAB (Minitab 1989). Results have been considered statistically significant when $P < 0·10$.

RESULTS

Nitrogen offtake

Over all sites, fertilizer N increased N_{off} by between 36 and 97 kg/ha (Table 2). At eight sites, N_{off} from AN was greater ($P < 0·10$) than from urea. Six of these sites were on chalk soils, the other two (sites B5 and C1) were of loamy sand texture and were the most coarse-textured soils in the study. The difference in N_{off} between fertilizer types was largest (*c.* 10 kg/ha) at sites B5 and C10, where N_{off} was greater from AN. At four sites (B7, B9, C13 and D2) mean N_{off} was as great, or greater, from urea. The greater recovery of urea at these sites was not clearly related to soil type or pH but none of the soils at those four sites was classified as chalk, or coarse sandy. When averaged across all sites and N fertilizer rates and application times, N_{off} was *c.* 3 kg/ha greater for AN than from urea (Table 2). Splitting the main N application did not affect N_{off} from AN but increased mean N_{off} from urea by *c.* 1·5 kg/ha (Table 2). The magnitude of these effects varied, depending upon site and amount of N applied.

Table 2. *Mean grain nitrogen offtakes (kg/ha) from experiments in England and Wales 1983–85 to compare the effectiveness of urea and ammonium nitrate as sources of fertilizer nitrogen for cereals*

Fertilizer N applied (kg/ha)	Control	Ammonium nitrate Single	Ammonium nitrate Split	Urea Single	Urea Split
0	54·3				
100		98·8	101·5	97·2	97·5
140		116·8	115·9	110·8	112·3
180		129·2	128·5	125·7	126·5
220		139·0	138·2	133·6	135·0
260		144·1	146·2	139·9	141·9
300		150·6	144·9	146·5	149·6
Mean		129·8	129·2	125·6	127·2
Mean		129·5		126·4	
S.E. (674 D.F.)			10·02		

Table 3. *Mean urea relative grain nitrogen offtake (URN_{off}, (%)) and mean urea relative yield (URY (%)) from experiments in England and Wales 1983–85 to compare the effectiveness of urea and ammonium nitrate as sources of fertilizer nitrogen for cereals*

Soil	Chalk	Non-chalk	Mean
URN_{off}			
Single application	96·2	97·3	96·8
Split application	96·9	99·3	98·3
Mean	96·6	98·3	
S.E. (48 D.F.)	3·56		
URY			
Single application	98·5	99·6	99·1
Split application	98·7	100·7	99·9
Mean	98·6	100·2	
S.E. (48 D.F.)	2·60		

In calculating URN_{off} (and URY) the N rates were meaned since they were common across all sites and since at no site was there a significant interaction between fertilizer type and N rate for N_{off}: at only one site was there a significant interaction in respect to yield.

Overall, urea was 97·5% as effective as AN, but the URN_{off} was less on chalky soils (Table 3). Splitting the main N top-dressing had no effect on URN_{off} (Table 3).

Influence of rain and soil temperature on N uptake

When the fertilizers were applied as a single main application, straight-line regression on rainfall on the day of application accounted for almost as much of the variance in URN_{off} as a corresponding regression on cumulative rainfall up to 4 days after application (16 and 19% respectively). However when the main dressing was split, only the regressions on rainfall on the day of application of the first dressing accounted for any of the variance in URN_{off} (7%). On chalk soils, the amount of variance in URN_{off} explained by the regressions on cumulative rainfall increased up to 5 days after application (54%, Table 4). For other soil types, little of the variance in URN_{off} could be accounted for by regression on rainfall after the day of application.

Herlihy & O'Keeffe (1987) found accumulated temperature (T) up to 10 days before and 60 days after urea application influenced the effectiveness of urea applied in early spring to grassland. In these experiments, temperatures were taken from the nearest Meteorological Office weather station. Straight-line regression on T 10 or 5 days before, and 5, 10, 15, 20, 30, 40 and 60 days after application accounted for almost none of the variance in URN_{off} when urea was applied in a single application. However, when applied as a split application, similar regressions on various measurements of T accounted for up to 42% of the variance in URN_{off} on chalk soils (Table 5), but little or none of the variance in URN_{off} in other soil types or overall. Simple multiple regression on variables that had been found to influence URN_{off} significantly did not account for any more of the variance in URN_{off} than the regressions on single variables.

Table 4. *Straight line regressions of urea relative N offtake* (URN_{off}) *on rainfall on the day of fertilizer N application* (*day1*) *and up to 4 days after, from experiments in England and Wales 1983–85 to compare the effectiveness of urea and ammonium nitrate as sources of fertilizer nitrogen for cereals on chalk soils and other soils*

	Equation	S.E.	R^2 (%)	P	D.F.
Chalk soils (single applications)					
Rainfall day 1 (rd1)			6·7	0·223	9
Cumulative rainfall d1 and d2 (crd2)	95·0 + 1·04 crd2	0·86/0·390	37·9	0·026	9
Cumulative rainfall d1-d3 (crd3)	95·1 + 0·33 crd3	0·80/0·111	43·9	0·016	9
Cumulative rainfall d1-d4 (crd4)	95·0 + 0·29 crd4	0·81/0·098	44·3	0·015	9
Cumulative rainfall d1-d5 (crd5)	94·7 + 0·32 crd5	0·78/0·090	53·5	0·006	9
Other soils (single applications)					
Rainfall day 1 (rd1)			13·0	0·102	13

Table 5. *Straight-line, and simple multiple regressions of urea relative N offtake* (URN_{off}) *from split fertilizer applications on accumulated air temperature before or after the first fertilizer N application* (*T1*) *or the second fertilizer N application* (*T2*), *chalk soils only from experiments in England and Wales 1983–85 to compare the effectiveness of urea and ammonium nitrate as sources of fertilizer nitrogen for cereals*

Days before (−) or after (+)	Equation	S.E.	R^2 (%)	P	D.F.
−10	102 − 0·06 T2	1·9/0·022	38·3	0·025	9
−5	101 − 0·10 T2	1·7/0·037	36·7	0·029	9
+5	102 − 0·11 T2	2·5/0·051	27·5	0·050	9
+10	106 − 0·05 T2 − 0·06 T1	3·1/0·029/0·025	42·0	0·046	8
+15	104 − 0·01 T2 − 0·04 T1	3·3/0·025/0·018	36·8	0·065	8

Apparent fertilizer recovery

The two-straight-line model of N offtake was used to estimate AFR at N_{opt}, which was *c.* 0·40 for both AN and urea. Splitting the fertilizer application had no effect on AFR, which was similar for both soil types (Table 6). In this data set, AFR was toward the smaller end of the range observed by Bloom *et al.* (1988). Those few sites where AFR was > 50% had no properties in common likely to explain the greater AFR observed. Little or none of the variance in AFR of either AN or urea could be accounted for by straight-line regression on rainfall in the days on, or immediately after, fertilizer application.

Table 6. *Apparent fertilizer recovery* (*AFR*) *in experiments in England and Wales 1983–85 to compare the effectiveness of urea and ammonium nitrate as sources of fertilizer nitrogen for cereals*

	Fertilizer			
	Ammonium nitrate		Urea	
Soil type	Single	Split	Single	Split
Chalk	0·45	0·42	0·42	0·45
Non-chalk	0·41	0·41	0·38	0·39
S.E. (55 D.F.)		0·088		

Grain yield

Fertilizer N increased grain yield at all sites by between *c.* 1·8 and 6·7 t/ha (Table 7). At three sites (B6, B8 and C7), all on chalk soils, yield was greater with AN, while at two sites (B9 and C13) yield was greater from urea. However, when averaged across all sites there was only a small (*c.* 0·03 t/ha), non-significant increase in yield from using AN. There was no yield benefit from splitting the main fertilizer N application. Mean URY was 99·5%, being greater in non-chalk soils (Table 3). As with N_{off}, splitting the main N application did not increase URY.

Table 7. *Mean grain yields (t/ha at 85% DM) from experiments in England and Wales 1983–85 to compare the effectiveness of urea and ammonium nitrate as sources of fertilizer nitrogen for cereals*

Fertilizer N applied (kg/ha)	Control	Ammonium nitrate Single	Ammonium nitrate Split	Urea Single	Urea Split
0	4·37				
100		6·70	6·73	6·68	6·68
140		7·33	7·35	7·12	7·21
180		7·66	7·53	7·55	7·55
220		7·73	7·68	7·80	7·68
260		7·82	7·82	7·83	7·78
300		7·96	7·72	7·85	7·91
Mean		7·53	7·47	7·47	7·47
		7·50		7·47	
S.E. (674 D.F.)		0·456			

Grain nitrogen concentration

Grain N concentration was *c.* 0·05% greater when AN was used compared with urea, except at N application of 300 kg/ha (Table 8). This effect was found at most sites; at only four sites were grain N concentrations greater where urea had been used.

Fertilizer nitrogen requirement for optimum yield

Overall, N_{opt} was similar for both types of fertilizer (Table 9) and was not affected by splitting the main fertilizer N application. However N_{opt} was *c.* 72 kg/ha greater on chalk soils than on others. This greater requirement of cereals grown on chalk soils for fertilizer N has been observed by other workers (e.g. Harrison 1995). At *c.* 7·85 t/ha, Y_{opt} was unaffected by fertilizer type, timing of application or soil type (Table 9).

Table 8. *Mean grain nitrogen concentrations (% of DM) from experiments in England and Wales 1983–85 to compare the effectiveness of urea and ammonium nitrate as sources of fertilizer nitrogen for cereals*

Fertilizer N applied (kg/ha)	Control	Ammonium nitrate Single	Ammonium nitrate Split	Urea Single	Urea Split
0	1·68				
100		1·74	1·77	1·72	1·72
140		1·88	1·87	1·84	1·84
180		2·00	2·03	1·97	1·98
220		2·14	2·14	2·03	2·09
260		2·18	2·22	2·13	2·17
300		2·25	2·23	2·22	2·24
Mean		2·03	2·04	1·98	2·01
		2·04		1·99	
S.E. (674 D.F.)		0·107			

Table 9. *Mean requirement of fertilizer for optimum yield (N_{opt} (kg/ha)) and yield at the optimum (Y_{opt} (t/ha)) from experiments in England and Wales 1983–85 to compare the effectiveness of urea and ammonium nitrate as sources of fertilizer nitrogen for cereals*

Soil type	Fertilizer Ammonium nitrate Single	Fertilizer Ammonium nitrate Split	Fertilizer Urea Single	Fertilizer Urea Split
N_{opt}				
Chalk	245	244	297	260
Non-chalk	189	177	201	185
S.E. (66 D.F.)		63·0		
Y_{opt}				
Chalk	7·82	7·85	7·97	7·75
Non-chalk	7·76	7·70	8·02	8·03
S.E. (66 D.F.)		1·62		

DISCUSSION

Nitrogen offtake

Urea has been considered to be less effective than other N fertilizers, due to N loss by ammonia volatilization, especially when used on soils of high pH or low CEC (Terman 1979). Yet in these experiments, while mean N_{off} was less from urea than from AN, the difference was small and was only significant at eight out of 26 sites. Moreover, regressions on pH or % $CaCO_3$ accounted for little or none of the variation in URN_{off}, for both single and split timing. Because we concentrated on calcareous soils, the range of soil pH was limited in this study. Only four sites were of pH < 6·5 and two of these (C1 and C13) were also of sandy texture. However, mean URN_{off} for these four soils was 97·9, increasing from 96·2 to 99·7 when the main application was split, and was therefore little different from the other sites.

The mean URN_{off} at five sites of loamy sand or sandy loam texture was 96·5%, the same as that on sites with chalk soils. In contrast to chalks, however, splitting the N application on sands increased URN_{off} from 95·1 to 97·9%. This suggests that a different mechanism could account for the lesser URN_{off} on these soil types. On sands, losses are potentially large because of the low CEC (Whitehead & Raistrick 1993), but the soil colloids may be adequate to adsorb ammonium ions released by urea hydrolysis when the dressing is split. However, while these data, like those of Lloyd (1992) and Chaney & Paulson (1988), suggest that urea effectiveness is not simply related to soil texture or pH, the relative efficiency of urea is

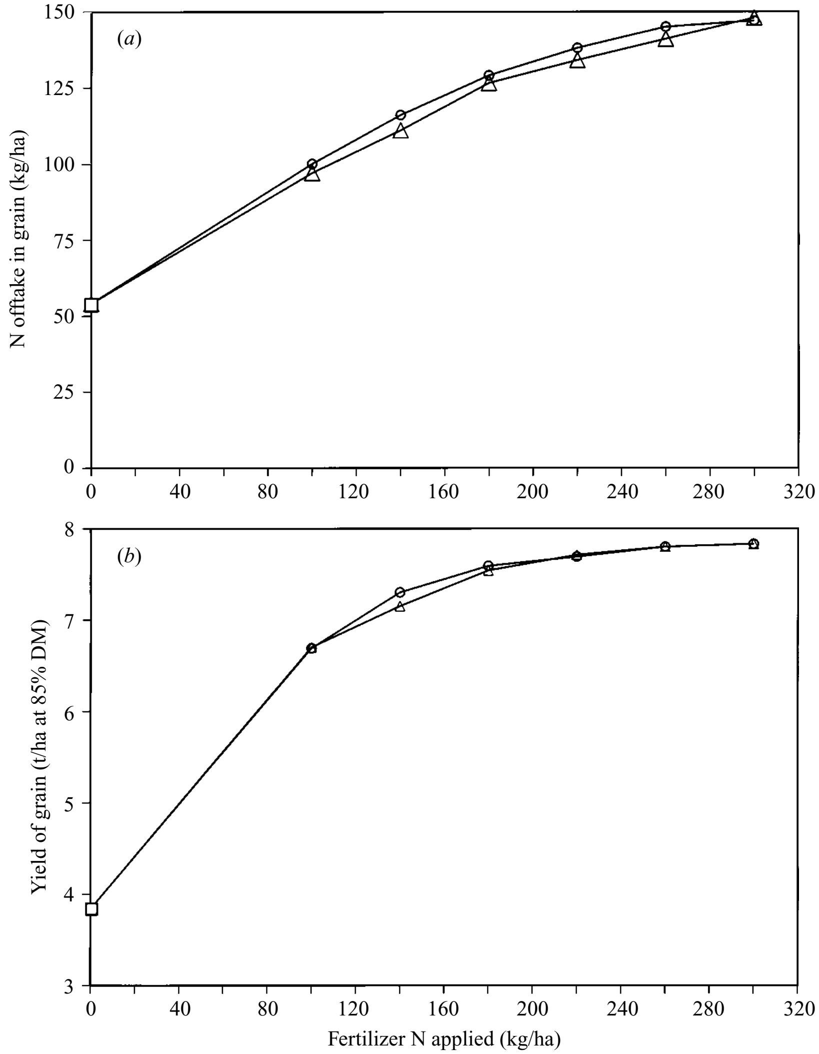

Fig. 1. Responses to fertilizer N applied as urea (△) or ammonium nitrate (○) from 26 sites in England and Wales 1983–85 to determine the effectiveness of urea and ammonium nitrate as sources of fertilizer N for cereals. Means of single and split applications. (*a*) N offtake in grain, (*b*) grain yield at 85% DM.

likely to be least on soils of small buffering capacity between initial soil pH and pH 8·0 (Stevens *et al.* 1989).

Grain yield

Despite the lesser N offtake in grain following urea application, there was no commensurate reduction in yield (Fig. 1). In particular, two sites (B5 and C1, where URN_{off} was 90·9 and 93·7 respectively) gave URY of 101·5 and 96·6 respectively. The differential behaviour of N from urea and AN (i.e. smaller grain N concentration from urea, but similar yields) suggest that urea is behaving in a manner analogous to an 'early' application of fertilizer N (Dampney 1987).

Some explanation is needed as to why these results differ from those of earlier workers. Court *et al.* (1964) and Rodgers *et al.* (1986) found evidence of ammonia and nitrite damage to crops, as well as of ammonia volatilization. The median date of N application reported by Chaney & Paulson (1988) was in early April, some 3 weeks earlier than in the experiments reported here. The application of urea to crops at a later growth stage may be advantageous. This is unlikely to be due to canopy absorption of volatilized ammonia, since only *c.* 2–3% of the ammonia emitted is absorbed by cereal canopies (Sommer *et al.* 1993). It is more likely that the larger, actively growing crops are less prone to direct damage than those at an earlier growth stage. Michael *et al.* (1970) found the deleterious effects of ammonia were reduced by an adequate supply of carbohydrate.

The choice between ammonium nitrate and urea

There does not appear to be any reason not to apply urea on non-chalk soils, since in these experiments URY was 100%. However, on chalk soils some reservations remain. The three sites on which yield was less were on chalk soils, and mean URY was 98·6%. It is useful to consider whether there are any measures that may be taken to increase URY on chalk soils.

Delaying application of half the main N dressing is not likely to be consistently effective in reducing ammonia loss and increasing recovery of urea N on chalk soils. If the soil is moist at the second application, ammonia loss may be greater if, as is likely, temperatures are greater and if no rain occurs. If, however, the soil is dry and hydrolysis does not take place, then uptake of N by the crop will be restricted. The best policy appears to be to delay part of the main application at that time only if dry weather is forecast and the soil is moist. If rain is imminent, or if the soil is dry, it would be prudent to apply all the main dressing at GS31.

Urea has in recent years been a less expensive form of N fertilizer than AN. Using a grain price of £100/t and an AN price of £130/t, the following break-even prices for urea can be calculated assuming a 7·5 t/ha crop receiving 200 kg/ha N.

Yield penalty AN – Urea	Urea break-even price £/t
0%	173
1%	153
2%	133
3%	114
5%	76

Thus with a yield penalty of *c.* 1·5%, if urea remains < £143/t it is a more cost-effective N fertilizer than AN.

For winter wheat, the likelihood of attracting premiums for breadmaking quality needs to be taken into account, since grain N concentration was on average smaller from urea than from AN. The implications of quality payments on the economics of applying N to winter wheat are complex (Sylvester-Bradley & George 1987), but a minimum of 2·14% N in grain DM is needed to achieve premium payments. At N_{opt} (*c.* 260 kg/ha on chalk soils and *c.* 190 kg/ha on other soils), a milling premium would have been realised at less than half the sites: 11 using AN and nine using urea. Thus, despite the reduced grain N concentration from urea, in practice the choice of fertilizer N source made little difference to the chances of gaining a milling premium.

Premium payments for malting barley are paid if grain N% is < 1·85, and reach a maximum if grain N% is < 1·55 (Lord & Vaughan 1987). Most of these experiments were carried out using wheat, so the implications of fertilizer N choice must be conjectural, but since urea produced grain of smaller %N it may be a better source of N than AN for crops grown for malting. At current recommended N rates (Anon. 1994*b*) for winter barley grown for malting (120 kg/ha for chalk soils, 110 kg/ha for other soil types), grain N concentrations were < 1·85% at most sites: 18 using AN and 19 using urea. Only three crops, one using AN and two using urea, had grain N of < 1·55%. Thus despite the smaller overall grain N% from using urea, there appears to be little benefit in using it to obtain a malting premium.

We conclude, therefore, that urea is a satisfactory source of fertilizer N for cereals, even on chalk soils.

The authors wish to thank all the ADAS colleagues who conducted these experiments, as well as F. M. Seeney, D. Hudson, S. J. Clark and D. R. Jackson, for help with the statistical analyses. We are also particularly grateful to L. V. Vaidyanathan for initiating this series of experiments. Financial support for this work from the Ministry of Agriculture, Fisheries and Food is gratefully acknowledged.

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