Differences in rainfall and temperature define the use of different types of nitrogen fertilizer on managed grassland in UK, NL and Eire

D.W. BUSSINK[1]* AND O. OENEMA[2]

[1] Nutrient Management Institute (NMI), Research Station for Cattle, Sheep and Horse Husbandry PR, Runderweg 6, NL-8219 PK Lelystad, The Netherlands
[2] Department of Soil Science and Plant Nutrition, P. O. Box 8005, NL-6700 EC Wageningen Agricultural University, The Netherlands
* Corresponding author (fax: 31-320-241584; e-mail: d.w.bussink@pr.agro.nl)

Received 12 June 1996; accepted 13 November 1996

Abstract

There are distinct differences between the Netherlands (NL) and the United Kingdom (UK) in the use of urea (U) and (calcium) ammonium nitrate ((C)AN) fertilizers on grassland. It has been known for some time that rainfall and temperature affect NH_3 volatilization from U and its agronomic efficiency. This study aimed (i) to examine how rainfall and temperature pattern in NL and UK relate to the observed U efficiency, and (ii) to provide a simple decision support model for farmers to enable them to choose the most appropriate N fertilizer. This study is based on straight forward and uniform statistical analysis (residual maximum likelihood) of existing data from numerous field trials.
The agronomic efficiency of U compared to CAN in field trials was expressed as (i) urea relative (N) yield (UR(N)Y), and (ii) apparent-urea relative (N) yield (AUR(N)Y).
In NL, URY did not significantly differ from 100% on peat grassland. Mean URY on sand and clay was 95%, in both cases. Mean seasonal AURY and AURNY for the summed data of sand and clay soils was 92.3 and 86.4%, respectively, without significant differences between first and later cuts. There was no significant improvement of AUR(N)Y in the last decades. In the first cut, mean AURY was lower than in En (100.9%) and NI (100.2%). Differences in efficiency between countries could be described by short-term rainfall and temperature. By aggregating NL, NI and En data a simple regression equation was derived:

$$AURY = 89.48\ (\pm 0.781) + 2.188\ (\pm 0.148) * R3 - 1.091\ (\pm 0.070) * T3$$

(R3 and T3; rainfall amount and average temperature within three days after fertilizer application, respectively). The decision support model based on this equation showed that under prevailing NL weather conditions it will be profitable for the farmer to apply U instead of CAN, for the first and second cut, only once every 5 and 7 years, respectively, because R3's exceeding 6 and 9.5 mm are required.

Keywords: urea, calcium ammonium nitrate, grassland, fertilizer efficiency, rainfall, temperature

Introduction

In Western Europe, grasslands are intensively managed and supplied with relatively large amounts of N fertilizer. Ammonium nitrate ((C)AN) based fertilizers are by far the dominant (more than 90%) N fertilizers for grassland in the Netherlands (NL). By contrast, in the United Kingdom (UK) and especially Eire, urea (U) based fertilizers have a significant share in the use of N fertilizer on grassland. Major reasons for use of U based fertilizers are the relatively low price, the high N content and the suggested lower susceptibility for NO_3^- leaching, denitrification (Jordan, 1989) and N_2O emission compared with (C)AN (Velthof *et al.*, 1996). Major objections for usage of U based fertilizers are the large potential for NH_3 volatilization (Freney *et al*, 1983) which on grassland can be as high as 60% of the applied N (Velthof *et al.*, 1990; Black *et al.*, 1987; Titko *et al.*, 1987; Kunelius *et al.*, 1987), the lower maximum yield (Watson *et al.*, 1990; Van Burg *et al.*, 1982) and the soil acidifying effect (Van Burg *et al.*, 1982). The general perception of the farmer is that U has a more uncertain effectiveness than CAN. In a review study, Watson *et al.* (1990) concluded that there was no evidence to indicate that U is significantly more variable than CAN for spring grass production in UK and Eire. There were large variations in the agronomic efficiency of both U and CAN when applied to grassland in spring. However, U was slightly less-effective than CAN in summer. Comprehensive field trials in NL, showed that over the whole season U was on average 15% less effective than CAN (Van Burg *et al.*, 1982). These somewhat contrasting conclusions suggest significant differences in environmental conditions, and thereby in the effectiveness of U relative to CAN, between UK and NL.

Weather conditions such as temperature and rainfall have a significant effect on the agronomic efficiency of N fertilizers. Rainfall and low temperatures after fertilizer application suppress NH_3 volatilization from U (Bouwmeester *et al.*, 1985; Black *et al.*, 1987; Freney *et al.*, 1983), thereby improving efficiency. In addition, rainfall increases NO_3^- leaching and denitrification from CAN, thereby decreasing CAN efficiency (Velthof *et al.*, 1996). It has been shown (Van Burg & Rauw, 1972; Lloyd, 1992) that rainfall amounts of about 5 mm within a few days after fertilizer application resulted in an equal efficiency of U and CAN. For much larger amounts of rainfall, U became more efficient than CAN. Because effects of rainfall and temperature on U efficiency are general, and omnipresent, we hypothesize that variation in rainfall and temperature patterns define the observed differences in U efficiency, between NL and UK/Eire.

As the present environmental and economical constraints force European farmers to reduce costs, increase nutrient efficiency and minimize nutrient losses, the choice of N fertilizer type becomes more important.

This study defines criteria to improve fertilizer N use efficiency on grasslands in UK, NL and Eire. Data from a large number of fertilizer trials on representative grassland sites in these countries were analyzed uniformly. These analyses were used to test whether differences in rainfall and temperature patterns define the differences in U efficiency between these countries. Because experiments were carried out in different years, we first tested whether there is a general increase in agronomic efficiency of U from the early fifties to the late eighties. This could be due to for example an improved fertilizer technology or a reduced biuret content in U (Watson *et al.*, 1990). Results were also used to construct a simple model to help farmers to decide when U is profitable relative to AN-based fertilizer.

A list of abbreviations used in this paper is added in Annex 1.

Materials and methods

Available data and sources

Available data from representative grassland areas in western Europe were analyzed, i.e. datasets from NL, Northern Ireland (NI) and southern England (En). General information about the datasets is given in Table 1. Available trials for NL varied from testing a single application in spring to a single application in autumn at different locations all over NL. In some trials applications of U and CAN were compared over all the growing season. Generally, dry matter yield (DMY) per cut ranged from 1500 to 4000 kg ha^{-1}, with the largest yields in the older experiments. Data for NI (Stevens *et al.*, 1989) came from a trial in which during three years the effect of ten dates of application of CAN and U on DMY was studied in a randomized block experiment at four different sites. Fertilizer was applied at weekly intervals from 1 February to 5 April at 70 kg N ha^{-1}. At each site two control plots within each block received no N. Treatments were replicated three times (three blocks). The first cut was mown for all treatments on the same day, at the end of April. Within two days CAN and U were re-applied (50 kg N ha^{-1}). The second cut was mown, at the end of May.

Data for southern En came from a four years old experiment (Peake, pers. comm.) in which DMY response of the first and second cut was determined. The DMY of the first and second cuts ranged from 5 to 7 and from 3 to 5 ton ha^{-1}, respectively.

Generally, the sites of the trials differed each year. In total, 244 treatment data sets (of which 100 for the first cut) were analyzed, the control treatments excluded.

Rainfall and temperature data were gathered for the trials in NL and NI for 10 days before N application up to mowing. The data came from official weather stations nearby the experimental sites. For En rainfall data within two days after application and average temperatures were available.

To predict the chance of a certain amount of rainfall after U application, probability curves were derived using rainfall statistics of NL in spring (period of 1930–1960), as an example. The probability of an amount of 'X' mm within 'Z' days was calculated.

Comparison of fertilizer N trials

From a farmer's point of view, the effect of applied N on the yield of metabolizable energy or DM has to be considered rather than the effect on total herbage N yield (NY). However, from an environmental point of view the fraction fertilizer N recovered by the crop is important, as the remaining N is susceptible to losses. We decided

to compare U and CAN on, both DMY and NY basis.
The efficiency of U and CAN in field trials with respect to DM yield can be expressed in terms of i) UEF (urea effectivity factor), ii) URY (urea relative yield) and iii) AURY (apparent-urea relative yield) i.e.,

$$\text{UEF} = \frac{\text{(CAN application needed to obtain yield X)}}{\text{(U application needed to obtain yield X)}} * 100\% \tag{1}$$

$$\text{URY} = \frac{\text{(DMY with U)}}{\text{(DMY with CAN)}} * 100\% \tag{2}$$

$$\text{AURY} = \frac{\text{(DMY with U)} - \text{(DMY of 0 N plot)}}{\text{(DMY with CAN)} - \text{(DMY of 0 N plot)}} * 100\% \tag{3}$$

Replacing DMY by NY in Equations (2) and (3) gives i) URNY (urea relative NY) and ii) AURNY (apparent-urea relative NY).

Probably, the most contrasting way (difference from 100%) of testing fertilizers is by UEF, followed by AURY and URY, as is demonstrated in Figure 1. The first two ways correct for the yield obtained at the control treatment. However, AUR(N)Y and UR(N)Y were mainly used in this paper, because i) most of the experiments did not contain enough N levels to apply the UEF method and ii) unless the maximum yield level for both fertilizers are the same UEF becomes biased (van Burg *et al.*, 1982). In the case of a low DMY or NY at the 0 N plot, UR(N)Y approaches AUR(N)Y. When there is no difference between the U and CAN fertilizers, AUR(N)Y and UR(N)Y are 100%.

Statistical analyses

Our dataset with N fertilizer trials (Table 1) contains information on treatment effects in similar experiments conducted at different times and places. To combine this information on treatment effects and to obtain information on sources and size of variability in the datasets we have to use the method of residual (or restricted) maximum likelihood. To do this we used the REML algorithm of the statistical package GENSTAT (Anonymous, 1994).

Models

The NL data were used to test whether there has been an increase of U efficiency in time and, also during the season using a linear mixed factorial model (Table 2 (A)).

To test whether differences in rainfall and temperature patterns adequately explain the observed differences in agronomic U efficiency and U use between NL, NI and En, we used similar linear, mixed models (Table 2). The NL model included 19 parameters including interactions, the En model only 5. This difference was due to the fact that inclusion of more parameters did not lower the deviance significantly or was not possible because no information was available (i.e. for En there was no information about number of growing days and temperature).

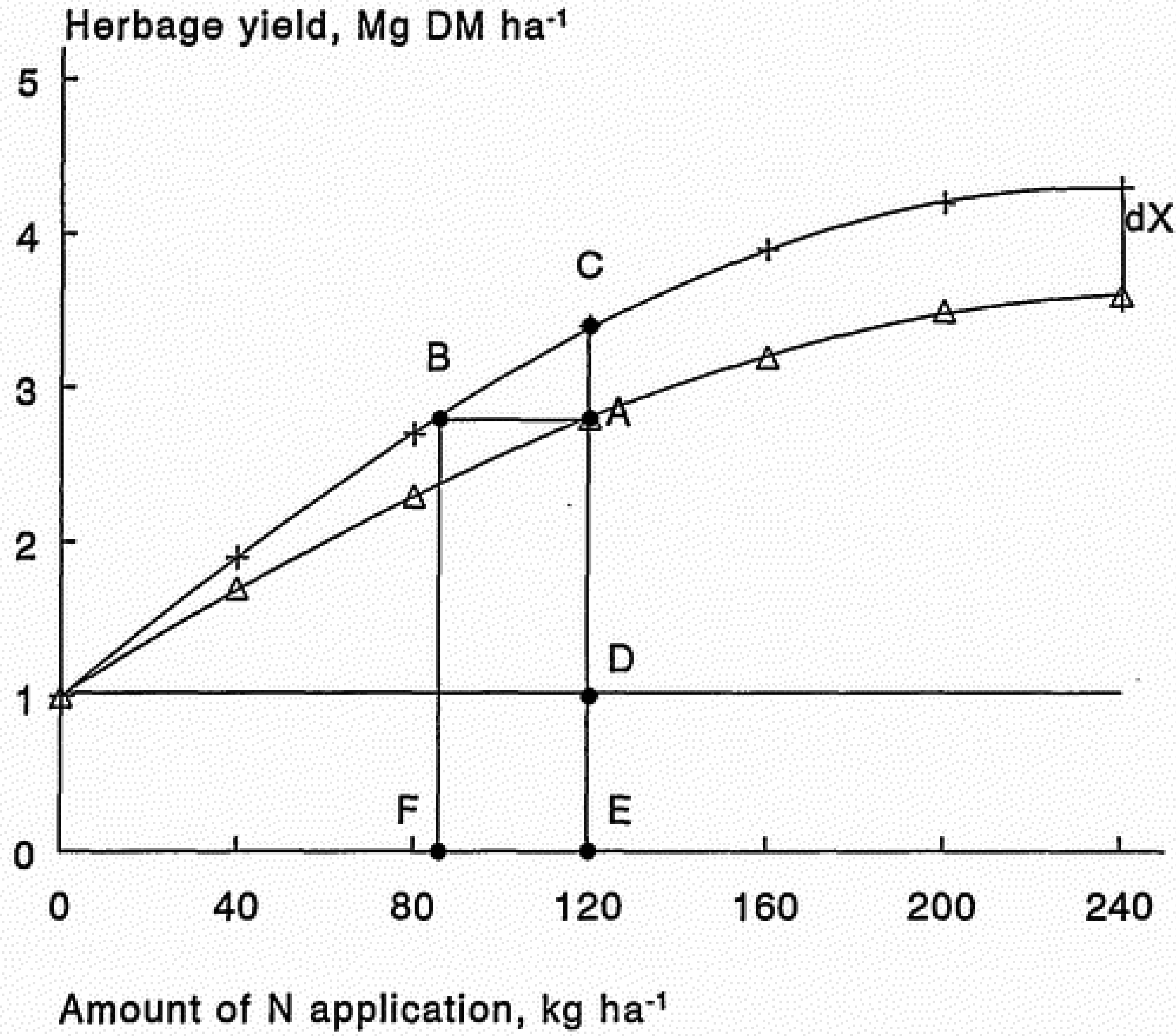

Figure 1. A schematic representation of how to estimate UEF (Urea Effectivity Factor), AURY (Apparent-Urea Relative Yield) and URY (Urea Relative Yield). UEF is 100 × F/E = 72%, AURY is 100 × (A-D)/(C-D) = 75%, URY is 100 × A/C = 82% and dX is the yield difference between CAN (+) and U (Δ) at maximum yield.

Results

NL data; effects of soil type, period of trial execution, harvesting day and amount of N applied

The URY frequency distributions shown in Figure 2 depict significant variations. Mean URY differed from 100% on sand and clay soils, but not on peat soils. These results were confirmed by statistical analysis using model NL-A (Table 2), suggesting that the agronomic efficiency of U was less than that of CAN on sand and clay but not on peat soils. Peat soils were excluded from further analysis because of the limited data. The apparent N recovery in these experiments was low. The 'prediction' with REML was 56% and 48% for CAN and U, respectively.

Table 1. Datasets from NL, NI and En used in statistically analysis.

Data sets	Sites	Period	Number of trial data	Soil types	N-applied kg ha^{-1} cut^{-1}	Number of cuts	Parameters recorded
NL							
Oostendorp & Boxem (pers. comm.), Boxem (pers. comm.) and NMI data (partly published by Van Burg *et al.* (1982))	28	1954, 1955, 1958, 1964–1967, 1970, 1971 1987–1989	1092*	sand, clay and peat	0–200	1 to 6	DMY and NY, daily temperatures and rainfall
NI							
Stevens *et al.*, (1989)	4	1983–1985	792	sandy-loam, clay silty-clay-loam and clay-loam	70, 50	1 and 2	DMY and NY, daily temperatures and rainfall
En							
Peake, unpublished results	27	1985–1988	244*	silt-loam, sandy-loam, loam,sandy-clay, clay sandy-silt-loam, sandy-clay-loam and clay-loam	0–200	1 and 2	DMY, rainfall within three days after fertilizer application

* averaged over blocks

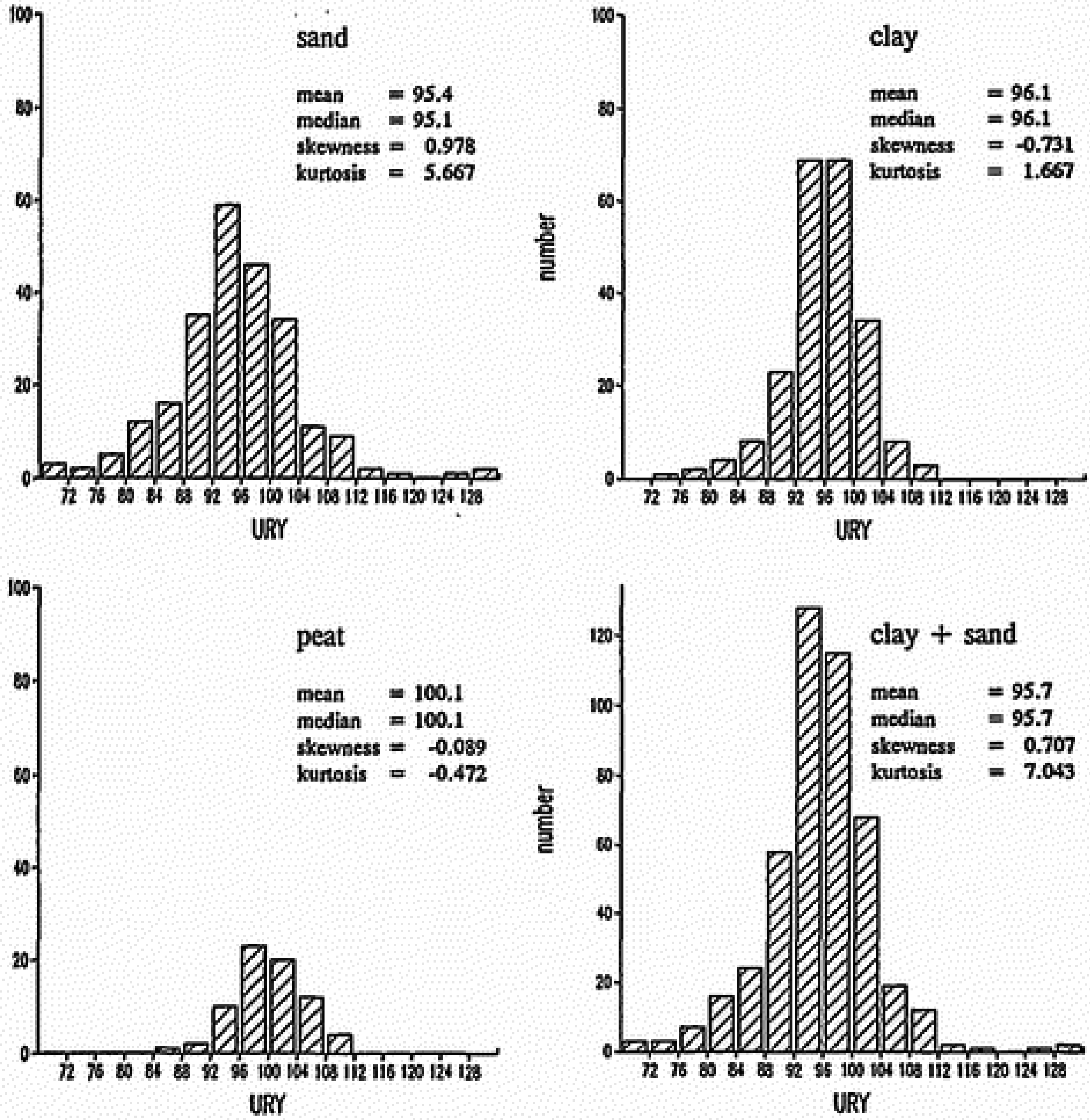

Figure 2. Frequency distribution of URY on sandy, clay, peat and sand+clay grassland of trials performed between 1954 and 1989 in NL.

Results presented in Table 3 indicate that AURY did not vary significantly between three classes of trials, grouped according to years. Trials carried out on sand and clay soils in the period 1954–1967 had similar AURY and also AURNY (data not shown) to the trials carried out in the period 1987–1989, suggesting no general increase in agronomic efficiency of U with time.

Results presented in Table 3 also indicate that AURY was affected neither by the harvesting day (HD), nor by the amount of applied N (applN). Similar results were obtained for AURNY (not shown). The fact that AUR(N)Y was independent of the number of cuts (HD) confirms the conclusions of Van Burg *et al.* (1982), except that a decreasing AURY with an increase in amount applN was not confirmed in the present study.

Reducing model NL-A (Table 2) to only the significant terms finally resulted in

Table 2. The general linear mixed models used to analyze NL, NI and En data, showing that model A for NL is a factorial model.

	NL		NI	En
	A	B		
μ	x	x	x	x
applN	x			
FT	x	x	x	x
HD	x			
mT		x	x	
Nappl		x		
NoGD		x	x	
RBy		x		
Rx		x	x	x
tR		x		
Tx		x	x	
ST*	x		x	
YR	x			
$(NoGD)^2$		x	x	
$(Nappl)^2$		x		
$(Rx)^2$		x		x
$(RBy)^2$		x		
FT.Nappl		x		
FT.Rx		x	x	x
FT.Tx		x	x	
Nappl.NoGD		x		
Nappl.tR		x		
Nappl.Rx		x		
NoGD.Rx			x	x
FT.NoGD.Rx		x	x	
remaining variance divided in variance components (ε) for				
ε_s (site)	x	x	x	
ε_y (year)	x	x	x	x
ε_{sy} (site.year)	x	x	x	
ε_{sb} (site.block)			x	
ε_{ysb} (site.year.block)			x	
ε_{yp} (year.pair)			x	
units	x	x	x	

μ constant (kg ha^{-1} yr^{-1})
applN factor 'amount of applied N (kg ha^{-1}), divided in 3 classes (Table 3)
FT factor 'fertilizer type', being U or CAN
HD factor 'harvesting days' divided in 4 classes (Table 3)
Nappl 'amount of N applied' (kg ha^{-1})
NoGD number of growing days (day)
mT 'mean temperature' between time of fertilization and cutting (°C)
RBy 'amount of rainfall' within y days before fertilizer application (mm)
Rx 'amount of rainfall' within x days after fertilizer application (mm)
tR 'total rainfall' between time of fertilization and cutting (mm)
Tx 'average temperature' within x days after fertilizer application (°C)
ST factor 'soil type'; sand, clay and peat for NL (A), sand and clay for NL (B), 8 soil types for En
YR factor 'year', divided in 3 classes (Table 3)
units rest variance at the lowest level

Table 3. The predicted 'DMY response – DMY response of 0N plot' for CAN and U, 'difference in DMY' and 'AURY' as a function of the factors soil type (ST), periods of years (YR), periods of harvest days (HD) in day numbers, and amount of applied N (applN) in kg N ha^{-1} of 459 pairs of yield data obtained in NL between 1954 and 1989.

Factor	Predicted 'DM yield – 0N' DM yield (kg ha^{-1})		Predicted 'DMY difference' (kg ha^{-1})	Average s.e.d.	Predicted AURY
	CAN	U			
FT[1]	1367[a]	1270[b]	106	27	92.3
ST					
sand	1354	1249	105	138	92.2
clay	1510	1377	130		91.2
YR					
1954–1967	1562	1444	118	317	92.4
1970–1973	1542	1387	155		89.9
1987–1989	1193	1109	84		93.0
HD					
< 136	883	759	124	254	86.0
136–151	1819	1700	119		93.5
152–181	1649	1513	136		91.8
>181	1378	1281	97		93.0
applN					
< 60	880	770	110	90	87.5
61–120	1504	1401	103		93.2
>120	1913	1769	144		92.5

$\sigma^2 = 1.126E+5$, $\sigma_y^2 = 9.74E+4$, $\sigma_{sy}^2 = 1.521E+5$ and $\sigma_{syr}^2 = 1.207E+5$

[1] Obtained after reduction model NL (A) (Table 2) to significant terms (superscripts a,b for $p \leq 0.001$)

'REML predictions' for the whole season for URY of 96%, for URNY of 93%, for AURY of 92% and for AURNY of 86%. All predictions were significantly different from 100% ($P < 0.001$). Because of the relative high DMY's and NY's at the control plots, UR(N)Y was markedly higher than AUR(N)Y.

NL data; effects of rainfall and temperature

Rainfall and temperature patterns during the trails may have contributed to the variation in URY. To test this, a more detailed analysis was performed based on model NL-B (Table 2). Data for the first cut and later cuts were analyzed separately, because of big differences in growing conditions. Analyses of DMY and NY response showed that best relationships were obtained with short-term weather conditions. After fertilizer application the amount of rainfall within three days (Rx = R3) and the average temperature during the first three days (Tx = T3) were significant. Before fertilizer application the amount of rainfall the preceding five days (RBx = RB5) and seven days (RBx = RB7) for the first and later cuts, respectively, were significant.

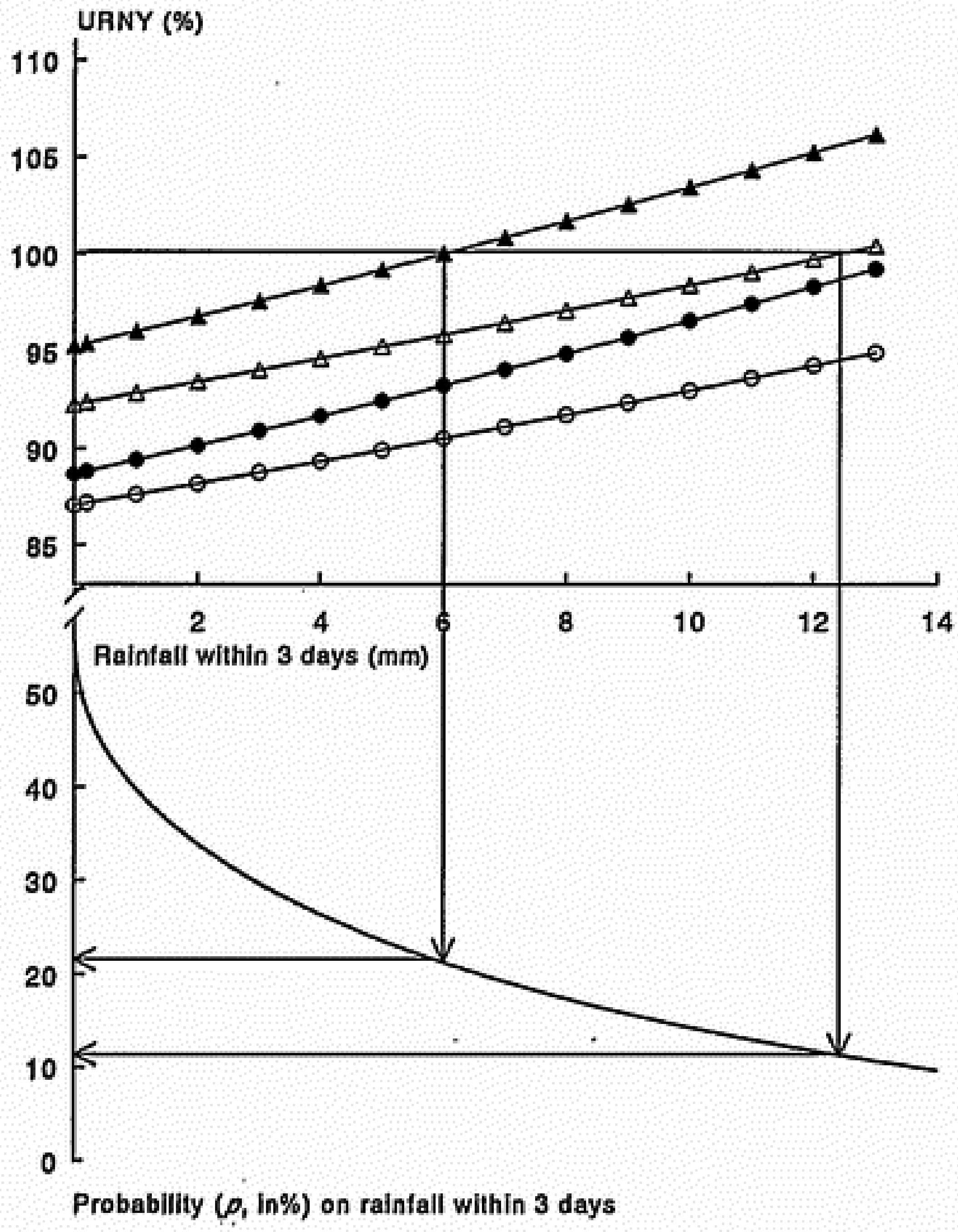

Figure 3. The effect of R3 for the first cut on AURNY for different N applications and mean temperatures the first three days after fertilizer application, (▲ = 60 kg N ha^{-1} and 8 °C, △ = 60 kg N ha^{-1} and 3 °C, ● = 100 kg N ha^{-1} and 8 °C, ○ = 100 kg N ha^{-1} and 3 °C). In addition the probability of R3, greater or equal than the amount plotted on the X-axis (is shown on the lower Y-axis).

Results of the DMY response models (Annex 2) indicate a significantly higher DMY than with CAN than U for the first cut (FT_{CAN} = 128 kg ha^{-1} cut^{-1}) and for later cuts (FT_{CAN} = 83 kg ha^{-1} cut^{-1}), which is in agreement with our earlier analysis. The DMY response of the first cut for U and CAN was positively related to total rainfall (tR) and mean temperature between fertilizer application and harvest (mT) and negatively to R3 (Annex 2). The DMY response of the later cuts was only related to short term weather conditions R3, T3 and RB7. The DMY response of first and later cuts showed no significant interactions between fertilizer type (FT) and weather conditions (i.e. FT_{CAN}.R3).

NY response of the first cut showed significant interactions between FT and R3, T3 and the N application rate (Nappl), respectively (Annex 2). An interaction between FT and applN was not found with model NL-A (Table 2), because all cuts were analyzed and weather parameters were not included. The summarized effects of these interactions (illustrated in Figure 3), show that AURNY decreases with Nappl, and increases with R3 and T3. In order to obtain an AURNY ≥ 100, rainfall amounts of ≥ 6.0 and ≥ 12.5 mm are necessary for N rates of 60 and 100 kg ha^{-1}, respectively. These amounts of rainfall are not very common. The rainfall probability curve (Figure 3) shows that the chances of these amounts in spring are ≤ 22% and ≤ 11%, respectively. At higher Nappl the chances of obtaining an AURNY ≥ 100% is even much lower than 10%.

For later cuts (Annex 2), there were no interactions between FT and R3, T3 and Nappl and it is predicted that use of U lowers N uptake with 5.9 kg ha^{-1} (FT_{CAN} = 5.9) under all conditions.

NI data; effects of rainfall and temperature

Stevens *et al.* (1989) found a significant DMY difference between U and CAN in the first cut in only three out of the 120 fertilizer applications. Because of this, the current dataset was aggregated, by averaging the results per cut over three years and 10 application times to reduce the variance in the experiments. The reduced dataset (4 sites, 3 blocks and 2 cuts) was analyzed (Table 4). The second cut showed a significant difference from 100% for URY, AURY and AURNY. For both cuts it appeared that URY, AURY and AURNY increased together with the amount of rainfall (Table 4).

Table 4. The URY, AURY, AURNY and cumulative rainfall averaged over three years and 10 application times for the first and second cut of the NI experiment of Stevens *et al.* (1989).

Site	URY %	AURY %	AURNY %	Cumulative rainfall (mm)
Cut 1				*Feb, March and April*
S1 (Crossnacreevy)	102.9	104.4	100.5	192
S2 (Hillsborough)	98.9	96.7	95.6	186
S3 (Castle Archdale)	101.2	103.5	106.4	218
S4 (Greenmount)	98.5	96.6	95.0	182
Mean	100.1	100.2	99.5	
Cut 2				*May*
S1 (Crossnacreevy)	97.6	96.2	93.4	55
S2 (Hillsborough)	98.1	96.1	91.1	54
S3 (Castle Archdale)	101.3	103.6	102.5	63
S4 (Greenmount)	97.3	94.6	92.6	53
Mean	98.7*	97.4*	95.2**	

*,** different from 100 at $P \le 0.05$ and $P \le 0.01$, respectively

The effect of rainfall and temperature was tested in more detail using model NI (Table 2) for the whole dataset. Analysis of DMY response of the first cut showed interactions between FT and Rx, Tx, NoGD and Rx.NoGD (Annex 2). Short-term rainfall and temperature was best related to DMY response for Rx = R3 and Tx = T3. The difference in DMY and NY response between CAN and U is negatively related with T3 and R3.NoGD and positively with R3 and NoGD. The summarized effect of these interactions is illustrated in Figure 4.

En data; effects of rainfall

The data of Peake (pers. comm.) showed a significant higher DMY with CAN than with U. Predicted URY for the first cut was 99.1% and for the second cut 94.8%. Predicted AURY for the first cut was 100.9% and for the second cut 91.1%. Using model En (Table 2), we obtained a significant interaction between FT and R3 (Annex 2). With U application, DMY increased by, respectively, 10.74 (± 6.68) and 13.75 (± 7.76) kg ha^{-1} mm^{-1} rainfall in the first and second cut (Annex 4), respectively, compared with CAN. Including the factor soil type (ST) in the model gave a significant improvement, because DMY differed significantly between the ST's.

Combined data of NL, NI and En

The analysis thus far showed that agronomic U efficiency was affected by short-term rainfall and decreased with short-term temperature after fertilizer application. If rainfall and temperature patterns in NL, NI and En are different, then mean (A)UR(N)Y are also different in these countries. Aggregation of recorded R3 and T3 data in NL, NI and En clearly showed systematic mean differences (Table 5). In NL, low AUR(N)Y were found together with relatively low R3 and T3 in the first cut, and relatively large R3 and T3 in later cuts. Apparently, the increased R3 (which suppresses NH_3 volatilization) in later cuts was counteracted by the increase in T3 (which enhances NH_3 volatilization). In NI, a relatively large AURY was combined with relatively large R3 and modest T3 in the first cut. In the second cut mean T3 was higher, which resulted in a decrease in AUR(N)Y. High temperatures and little rainfall promote NH_3 volatilization from U and reduce N losses through denitrification and NO^-_3 leaching from (C)AN. Both counteracting processes lead to low AUR(N)Y.

Combining all trials and all cuts leads to the following relationships between AUR(N)Y and R3 and T3:

$$\text{AURY} = 89.48\ (\pm 0.781) + 2.188\ (\pm 0.148) * \text{R3} - 1.091\ (\pm 0.070) * \text{T3} \quad (R^2_{adj} = 98.9\%) \qquad (4)$$

$$\text{AURNY} = 81.72\ (\pm 1.93) + 3.665\ (\pm 0.366) * \text{R3} - 1.815\ (\pm 0.219) * \text{T3} \quad (R^2_{adj} = 97.6\%) \qquad (5)$$

These relationships clearly indicate that rainfall and temperature define the agronomic efficiency of U in a similar way in NL, NI and En.

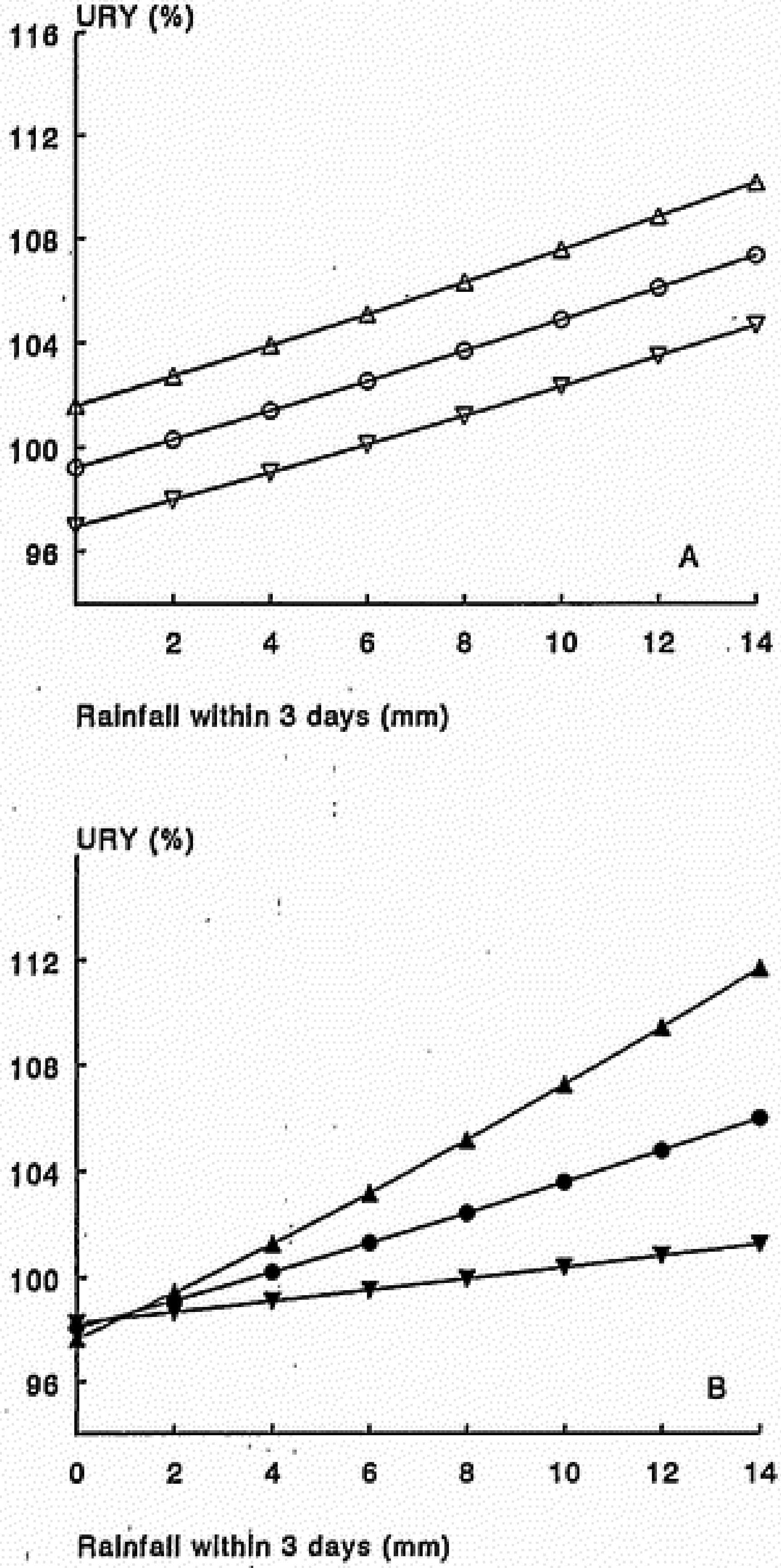

Figure 4. The effect of R3 on URY in NI for varying NoGD, A (△ = 80 day, ○ = 60 day, ▽ = 40 day) with T3 = 5°C, mT = 6°C and tR = 120 mm and for varying T3, B (▲ = 8°C, ● = 6°C, ▼ = 4°C) with NOGD = 60 day, mT = 6°C and tR = 120 mm), using the results of Stevens *et al.* (1989).

Economic evaluation of the use of (C)AN and U

The farmer's choice of the amount and type of N fertilizer to be used on grassland is an economic decision; he wants to maximize the difference between the harvesting

Table 5. The average AURY, AURNY and the average amount of rainfall and average temperature within three days after fertilizer application (R3,T3) in NL, NI and En.

Cut	AURY %	AURNY %	R3 (mm)	T3 °C	3 day periods without rain, (%)
NL					
First	92.3	86.4	3.63	4.67	15.6
Later	92.3	86.4	8.90	14.21	24.4
NI					
First	100.2	99.5	7.38	6.4	23.3
Second	97.3	95.2	7.42	9.1	16.7
En					
First	100.9	–[1]	8.94	–	10.0
Second	91.1	–	5.70	–	21.7

[1]) no data available

value (product quality in combination with yield) of herbage and the costs of fertilizer input.

To facilitate decision analysis, we developed an empirical relationship to predict the profitability of U use. This relationship is based on Equation 4, but includes also the effect on soil acidification of U use, relative to CAN use:

$$U_p = CAN_p + DM_p*(DMY_{fert}-DMY_{0N})*(0.8948 + 0.02188*R3 - 0.01091*T3)/Nappl + (-2.94 + 1/(\text{fraction of N contained in CAN}))*lime_p \quad (6)$$

with:

- U_p, CAN_p and DM_p are the prices of U-N, CAN-N and herbage DM (Dfl kg^{-1}), respectively.
- $DMY_{fert}-DMY_{0N}$ is the DMY difference between the fertilized and the 0N plot (kg DM ha^{-1})
- $lime_p$ is the price of the limestone contained in CAN (Dfl kg^{-1})

CAN contains limestone, which is valued in Equation 6. Furthermore, it is possible to value the differences in NH_3 volatilization, N_2O emission and NO_3^- leaching. These losses are unwanted. In the future, farmers could be charged for these losses, if data are available. However, at present there is not much evidence that fertilizer type affects N losses, let alone quantified estimates as a function of rainfall and temperature.

Examples of Equation 6 are shown in Figure 5. The calculations have been performed for DMY_{fert} and DMY_{0N} of 3000 and 1500 kg ha^{-1} cut^{-1}, respectively, in the first cut (T3 = 5°C) and second cut (T3 = 12°C). In NL one kg herbage DM has a value of Dfl. 0.20 and U is about Dfl. 0.15 kg^{-1} N cheaper than CAN (27%) (Anonymous, 1996). Figure 5 indicates that R3 must exceed 6 mm and 9.5 mm for the first and second cut, respectively, to obtain equal profits for U and CAN. In NL the probability of R3 > 6 mm and R3 > 9.5 mm is 20% and 15% for the first and sec-

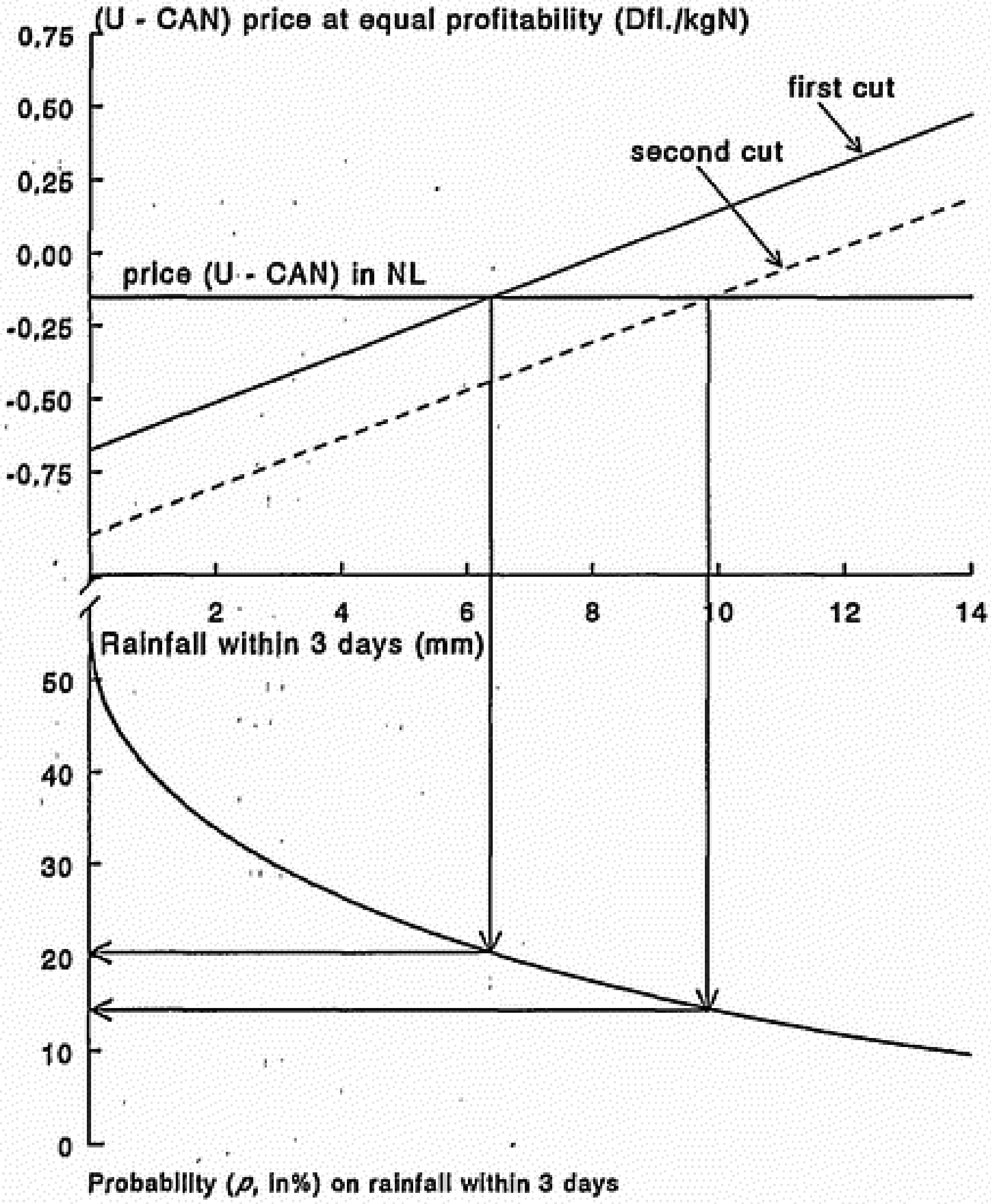

Figure 5. The effect of R3 on the price difference needed between U and CAN to obtain equal profits for different temperatures, based on NL and NI data.

ond cuts, respectively, indicating that use of U for those cuts is only profitable once every 5 and 7 years, respectively. Assuming that the R3 values in Table 5 for NI and En are representative for the whole of NI and En, then usage of U is profitable for the first cut, because R3 is > 6 mm (Figure 5). For later cuts it is generally not profitable to use U. Of course there are differences within a country in rainfall and temperature pattern during spring. Improving the rainfall probability curve by using data of local weather stations will greatly improve the accuracy of the predictions with Equation 6.

Discussion

Effects of rainfall and temperature

Straightforward analysis of NL, NI and En data showed that rainfall and temperature have a marked and uniform effect on the agronomic U efficiency. These results confirm other findings (e.g. Van Burg *et al.*, 1982; Black *et al.*, 1987; Herlihy and O' Keeffe, 1988; Watson *et al.*, 1990; Lloyd, 1992; Mahli, 1995). Thus far, however, no link has been made to the fact that rainfall and temperature patterns also determine the differences in observed efficiencies between countries. Our study clearly shows that rainfall and temperature not only define (A)UR(N)Y in field trials within a country but also the observed differences in the use of fertilizer types between countries. Therefore, the conclusion of Watson *et al.* (1990) that U is generally as good as CAN early in the growing season, but less-effective in summer for NW-Europe conditions is too strict.

No significant increase of (A)UR(N)Y over the last 35 yrs was observed (Table 3). Such an increase might have occurred because of changes in grassland management, fertilizer granule quality and/or variations in weather conditions. Data of 30–40 years of fertilizer trials are useful to test this provided the management of the trials is similar during the years. This was the case and was confirmed by statistical analysis. Improving fertilizer granule technology in the last decades (Anonymous, 1979), has resulted into more equal and less caking granules. This contributes to a better distribution of fertilizer on farms, but will hardly affect the distribution of fertilizer in trials with small plots and effects will therefore not be demonstrated.

For example, average R3 was 4.9, 5.3 and 7.7 mm and average T3 was 5.6, 10.5 and 13.5 °C during the periods 1954–1967, 1970–1973 and 1987–1989, respectively. Using Equation 4 this would give a mean AURY of 94, 89 and 91%, respectively, roughly the same variation as in Table 3.

We may conclude that (A)UR(N)Y values are similar in NL and UK where there are similar rainfall and temperature patterns. Variations in AURY between countries, during the season or between seasons can be mainly explained by these two variables.

Other important factors that may effect U efficiency

Van Burg *et al.* (1982) and Chaney & Paulson (1988) showed that UEF and URY decreased with Nappl increased, especially at high Nappl. Van Burg *et al.* (1982) found UEF's of 0.85 and 0.75 for Nappl of 70 and 140 kg N ha^{-1}, respectively. Lloyd (1992) found similar DMY increases per kg N applied with 80–160 kg N ha^{-1}. We found the same in our analysis. This suggests that URY decreases at high Nappl. Average Nappl for the first cut and later cuts was 110 and 80 kg ha^{-1} in NL and 70 and 50 kg ha^{-1} in NI. Nowadays, Nappl for the first cut and later cuts is decreasing and seldom exceeds 100 kg ha^{-1}. This may contribute to an improvement in U efficiency.

Results of Chaney & Paulson (1988) and Lloyd (1992) suggest that agronomic U effectiveness is different on calcareous compared with non-calcareous soils. The difference suggests that N losses from U through NH_3 volatilization are involved (ECE-

TOC, 1994). The higher agronomic effectiveness on peat soils compared to sand and clay soils may be due to a combination of low NH_3 volatilization from U and relatively large N losses from CAN through denitrification. Peat soils are wet and this favors the dissolution and diffusion transport of U into the soil, thereby reducing the risk of NH_3 volatilization. Wet soil conditions also promote denitrification, thereby reducing the amount of NO_3–N from CAN. As a consequence, CAN-N derived emissions of N_2O, an intermediate component in both denitrification and nitrification processes, are much larger on peat soils than on sand and clay soils (Velthof *et al.*, 1996). Denitrification measurements in NI by Jordan (1989) gave also much higher N losses from CAN than from U, especially under wet conditions. Data on peat soils should therefore be analyzed separately.

The form of N in fertilizers may also affect the efficiency of N fertilizers. Uptake of U by the crop is lower than the absorption of NH_3^- and NO_3^- (Bradley *et al.*, 1989). Within a few days (even at low temperatures) U is hydrolyzed to NH_4^+ (Gillman *et al.*, 1995). Then the main N forms present in U and CAN fertilized soil are NH_4^+ and NH_4NO_3, respectively. Perennial ryegrass uses NO_3-N more effectively than NH_4-N in DM production (Watson, 1988) and yields are highest when a mixture of NO_3^- and NH_4^+ is supplied (Haynes, 1986). This suggests that a lower uptake efficiency in addition to N losses via NH_3 volatilization may be therefore one of the reasons for the observed lower attainable maximum yield with U than with CAN (Van Burg *et al.*, 1982; Watson *et al.*, 1990).

Choice of fertilizer

With Equation 6, we obtained a simple decision support equation for farmers to enable them to choose between U and CAN, for spring application on grassland. In addition, the decision which N fertilizer to apply may also depend on the storage capacity at the farm. U requires less storage capacity than CAN because of its higher N content. Furthermore the cost of transportation from the retailer to the farmer may be lower for U than for CAN when distances are large. Equation 6 may therefore require some adaptations, depending on local circumstances.

Acknowledgements

The authors would like to thank dr. R.J. Stevens and dr. H. Peake who have kindly provided their datasets which have made this comparative study possible and G. André for his assistance with the statistical analysis. We thank Hydro Agri for funding this study.

References

Anonymous, 1979. Fertilizer manual. International Fertilizer Development Centre, Muscle Shoals, 353 pp.

Anonymous, 1994. GENSTAT 5, Release 3. Reference manual. Clarendon Press, Oxford, 796 pp.

Anonymous, 1996. Monthly Journal of Price Statistics. (In Dutch). LEI-DLO, Den Haag, 34–3, 31 pp.

Black, A.S., R.R. Sherlock & N.P. Smith, 1987. Effect of timing of simulated rainfall on ammonia volatilization from urea, applied to soil of varying moisture content. *Journal of Soil Science* 38:679–687.

Bouwmeester, R.J.B., P.L.G. Vlek & J.M. Stumpe, 1985. Effect of environmental factors on ammonia volatilization from a urea-fertilized soil. *Soil Science Society of America Journal* 49: 376–381.

Bradley, D.P., M.A. Morgan & P. O'Toole, 1989. Uptake and apparent utilization of urea and ammonium nitrate in wheat seedlings. *Fertilizer Research* 20: 41–49.

Chaney, K. & G.A. Paulson, 1988. Field experiments comparing ammonium nitrate and urea top-dressing for winter cereals and grassland in the UK. *Journal of Agricultural Science*, Cambridge 100: 285–299.

Freney, J.R., J.R. Simpson & O.T. Denmead, 1983. Volatilization of ammonia. In: J.R. Freney & J.R. Simpson (Eds.) Gaseous Loss of Nitrogen from Plant-Soil Systems. Developments in Plant and Soil Science, Volume 9, Martinus Nijhoff, The Hague, pp. 1–32.

Gillman, E., M.A. Morgan & M. Sherwood, 1995. Urease activity in the profile of pasture and tillage soils: Implications for urea leaching at low soil temperatures. *Biology and Environment: Proceedings of the Royal Irish Academy* 95B:111–118.

Haynes, R.J., 1986. Uptake and assimilation of mineral nitrogen by plants. In: R.J. Haynes (Ed.) Mineral nitrogen in the plant-soil system. Academic Press, Inc, London, pp. 303–378.

Herlihy, M. & W.F. O'Keeffe, 1988. Evaluation and model of temperature and rainfall effects on response to N sources applied to grassland in spring. *Fertilizer Research* 13: 255–267.

Jordan, C., 1989. The effect of fertiliser type and application rates on denitrification losses from cut grassland in Northern Ireland. *Fertilizer Research* 19: 45–55.

Kunelius H.T., J.A. Macleod & K.B. McCrae, 1987. Effect of urea and ammonium nitrate on yields and nitrogen concentration of timothy and bromegras and loss of ammonia from urea surface applications. *Canadian Journal of Plant Science* 67: 185–192.

Lloyd, A., 1992. Urea as nitrogen fertilizer for grass cut for silage. *Journal of Agricultural Science*, Cambridge 119: 373–381.

Mahli, S.S., 1995. Influence of source, time and method of application, and simulated rainfall on recovery of nitrogen fertilizers applied to bromegrass. *Fertilizer Research* 41: 1–10.

Stevens, R.J., H.I. Gracey, D.J. Kilpatrick, M.S. Camlin, D.G. O'Neill & R.J. McLaughlan, 1989. Effect of date of application and form of nitrogen on herbage production in spring. *Journal of Agricultural Science*, Cambridge 112: 329–337.

Titko, S., J.R. Street & Tj. Logan, 1987. Volatilization of ammonia from granular and dissolved urea applied to turfgrass. *Agronomy Journal* 79: 535–540.

Van Burg P.F.J. & G.J.G. Rauw, 1972. The N efficiency of urea on grassland (In Dutch). *Stikstof* 71: 466–475.

Van Burg, P.F.J., K. Dilz & W.H. Prins, 1982. Agricultural value of various nitrogen fertilizers; results of research in the Netherlands and elsewhere in Europe. Netherlands Nitrogen Technical Bulletin 13. Agricultural Bureau Netherlands Nitrogen Fertilizer Industry, 51 pp.

Velthof, G.L., O. Oenema, R. Postma & M.L. Van Beusichem, 1996. Effects of type and amount of applied nitrogen fertilizer on nitrous oxide fluxes of intensively managed grassland. *Fertilizer Research* (submitted).

Velthof, G.L., O. Oenema, J. Postmus & W.H. Prins, 1990. In-situ field measurements of ammonia volatilization from urea and calcium ammonium nitrate applied to grassland. *Meststoffen* 1/2: 41–46.

Watson, C.J., 1988. An assessment of granular urea/ammonium sulphate and urea/potassium nitrate fertilizers on nitrogen recovery by ryegrass. *Fertilizer Research* 18: 19–29.

Watson, C.J., R.J. Stevens, M.K. Garrett & C.H. McMurray, 1990. Efficiency and future potential of urea for temperate grassland. *Fertilizer Research* 26: 341–357.

Annex 1.

Used abbreviations

AN	= ammonium nitrate
applN	= 'amount of applied N' (kg ha^{-1}), divided into 3 classes
AURY	= apparent urea relative yield (%); 100 × ((DMY with U)-(DMY of 0 N plot))/((DMY with CAN) – (DMY of 0 N plot))
AURNY	= apparent urea relative N yield (%); 100 × ((NY with U)-(NY of 0 N plot))/((NY with CAN)-(NY of 0 N plot))
CAN	= calcium ammonium nitrate
DMY	= dry matter yield (kg ha^{-1})
FT	= factor fertilizer type, being U or CAN
HD	= factor 'harvesting days', in numbers of day, divided into 4 classes
mT	= 'mean temperature' between time of fertilization and cutting (°C)
N	= nitrogen
Nappl	= 'amount of N applied' (kg ha^{-1})
NY	= N yield (kg ha^{-1})
NoGD	= number of growing days (days)
RBy	= 'amount of rainfall' within y days before fertilizer application (mm)
REML	= restricted maximum likelihood
Rx	= 'amount of rainfall' within x days after fertilizer application (mm)
ST	= factor 'soil type', 3 types for Netherlands (sand, clay and peat) and 8 types for England
U	= urea
tR	= 'total rainfall' between time of fertilization and cutting (mm)
Tx	= 'average temperature' within x days after fertilizer application (°C)
UEF	= urea efficiency factor (%); 100 × (CAN application needed to obtain yield X)/(U application needed to obtain yield X)
URY	= urea relative yield (%); 100 × (DMY with U)/(DMY with CAN)
URNY	= urea relative N yield (%); 100 × (NY with U)/(NY with CAN)
YR	= factor 'years' (yr), divided into 3 classes

Annex 2.

DM yield (kg ha^{-1} cut^{-1}) and N yield (kg.ha^{-1} cut^{-1}) response models for clay plus sand grassland of the first and later cuts for the NL dataset.

Model terms	DMY model			NY model		
	U	CAN	*Se/Sed*	U	CAN	*Se/Sed*
Cut 1						
Constant	−17163			−157.6	−161.7	
main effect	0	128	*12.3*	0	9.65	*1.18*
Nappl		3.705*	1.554	0.4233	0.5213	*0.0360*
R3		−8.43	5.75	−0.0007	−0.6114	*0.2874*
T3				1.526	0.5682	*0.4854*
mT	978.0		33.5	17.10		0.94
tR	2.973		1.682			
NoGD	116.4		9.6	1.011		0.059
NoGD²	−0.558		0.0559			
Nappl.NoGD	0.1275		0.0314			
Nappl.tR	−0.0237		0.0101			
RB5				0.6561		0.2849
RB5²				−0.0198		0.0083
Later cuts						
Constant	4123			−22.41		
main effect	0	82.56	*38*	0	5.888	*1.12*
Nappl	7.86		0.8020	0.9272		0.0748
R3	−57.59		15.08	−0.1945		0.0735
R3²	−0.85		0.3228			
T3	−15.69		2.380	−0.1619		0.07062
tR						
NoGD	38.05		6.085	1.267		0.2443
NoGD²	−1.81		0.3900			
Nappl²	−0.0511		0.0087	−0.0022		0.0003
Nappl.NoGD				−0.0102		0.0024
Nappl.tR						
Nappl.R3	0.1747		0.0659			
NoGD.R3	1.956		0.4778			
RB7	−8.380		2.713	0.1125		0.0714
RB7²	−0.4071		0.1376	−0.0195		0.0038

* identical values for U and CAN are placed between the U and CAN column.
DMY first cut: $\sigma_e^2 = 3.00E+5$, $\sigma_y^2 = 3.84E+5$ and $\sigma_{syr}^2 = 1.24E+5$; VC= 11.3%; n=323
DMY later cuts: $\sigma_e^2 = 2.21E+4$, $\sigma_y^2 = 7.31E+4$ and $\sigma_{syr}^2 = 1.35E+5$; VC=11.4%; n=380
NY first cut: $\sigma_e^2 = 175.9$, $\sigma_y^2 = 259.2$ and $\sigma_{syr}^2 = 68.9$; VC = 8.5%; n = 197
NY later cuts: $\sigma_e^2 = 139.8$, $\sigma_y^2 = 62.1$ and $\sigma_{syr}^2 = 118.1$; VC = 12.0%; n = 376

Annex 3.

DM yield (kg ha^{-1} cut^{-1}) and N yield response models of the first cut for the NI dataset of Stevens *et al.* (1989).

Model parameters	DMY model			NY model		
	U	CAN	*Se/Sed*	U	CAN	*Se/Sed*
Constant	−293.9	−137.5		19.27	14.51	
main effect	0	1.906	*23.1*	0	−0.1792	*0.7338*
R3	−0.3530	11.41	*6.14*	0.0653	0.3414	*0.1951*
T3	−1.825	−29.05	*10.54*	−0.3155	−1.106	*0.3347*
NoGD	50.28	50.76	*1.49*	0.8670	0.8778	*0.0474*
R3,NoGD	−0.0095	−0.4143	*0.1322*	−0.0014	−0.0125	*0.0042*
mT	160.8*		27.3	3.976		0.865
NoGD^2	−0.3791		0.0329	−0.0071		0.0010

* identical values for U and CAN are placed between the U and CAN column.

DMY: $\sigma_y^2 = 1.69E+5$, $\sigma_s^2 = 4.62E+5$, $\sigma_{sy}^2 = 3.05E+5$, $\sigma_{sb}^2 = 1.28E+4$, $\sigma_{ysb}^2 = 4.51E+3$ and $\sigma_{ysbr}^2 = 9.61E+4$; VC = 13.4%; n = 720

NY: $\sigma_y^2 = 125$, $\sigma_s^2 = 485$, $\sigma_{sy}^2 = 114$, $\sigma_{sb}^2 = 18.3$, $\sigma_{ysb}^2 = 5.43$ and $\sigma_{ysbr}^2 = 96.9$; VC = 13.4%; n = 720

Annex 4.

DM yield (kg ha^{-1}) response models for the first and second cut of the En experiment of Peake (pers. comm.).

Model parameters	Cut 1 U	Cut 1 CAN	Cut 1 *Se/Sed*	Cut 2 U	Cut 2 CAN	Cut 2 *Se/Sed*
Constant	6543	6639		3429	3506	
main effect	0	−24.00	*44.16*	0	160.6	*54.53*
R3	−584.4	−595.1	*6.7*	86.67	72.92	*7.59*
Nappl	5.323*		1.522	5.009		2.426
$R3^2$	25.05		2.435	−4.74		2.882
$ST_{silt\text{-}loam}$				0		579.3**
$ST_{sandy\text{-}loam}$	−227		25.16**	−804.7		579.3**
ST_{loam}				670.6		579.3**
ST_{clay}	2680		25.16**	129.7		579.3**
$ST_{sandy\text{-}clay\text{-}loam}$	1893		25.16**	1070.1		579.3**
$ST_{clay\text{-}loam}$	0		25.16**	−796.7		579.3**
$ST_{sandy\text{-}clay}$				−188.0		579.3**
$ST_{sandy\text{-}silt\text{-}loam}$				741.8		579.3**

* identical values for U and CAN are placed between the U and CAN column.
** average Sed.
DM yield first cut: $\sigma_y^2 = 1.354E+4$, $\sigma_{yp}^2 = 1.898E+5$ and $\sigma_{ypr}^2 = 4.875E+4$; VC= 3.5% n=100
DM yield second cut: $\sigma_y^2 = 6.4E+3$, $\sigma_{yp}^2 = 6.257E+5$ and $\sigma_{ypr}^2 = 1.026E+5$; VC=7.6%; n=144