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Sixty years of Dutch nitrogen fertiliser experiments, an overview of the effects of soil type, fertiliser input, management and of developments in time

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Abstract

Data of Nitrogen fertilisation experiments of 1934 – 1994 have been analysed, using models for N uptake and DM yield. Both models were affected by fertiliser level, soil type, soil organic matter content, grassland use, cutting frequency, grassland renovation, white clover content and the N content analysis (Crude Protein or total-N). Effects on Soil Nitrogen Supply (SNS), Apparent Nitrogen Recovery (ANR) and Nitrogen Use Efficiency (NUE) are discussed.

Differences in SNS, ANR and NUE between sand and clay were small, SNS on poorly drained peat soil was 60 and 80 kg N per ha higher than on clay and sand, respectively, ANR on poorly drained peat soil was 7 and 10% lower. The NUE was similar on sand, clay and poorly drained peat.

ANR was low at low N application levels, due to immobilisation. ANR increased from 35% to 65% at application levels of 50 and 250 kg N per ha, respectively. At application levels of more than 250 kg N per ha, ANR decreased. NUE decreased from 45 to 29 kg DM per kg N with increasing N application levels of 0 and 550 kg per ha. It is suggested that for a good N utilisation a minimum N application of 100 kg N per ha should be used.

SNS increased by a mixed use of grazing and cutting with 27 and 40 kg N per ha for sand/clay and poorly drained peat respectively. ANR on sand decreased from 5 to 10% at applications of 200 and 500 kg N per ha and NUE decreased with 1–2 kg DM per kg N. The effect of grazing was stronger under pure grazing than with a mixed use of grazing and cutting.

Increasing the cutting frequency from 3 to 8 cuts per year had no effect on SNS, increased ANR with 0–20% and decreased NUE with 4–7 kg DM per kg N. The positive effect of the higher ANR compensated the lower NUE at application levels of 400 kg N per ha.

Changes in ANR over the last sixty years can be explained by changes in experimental conditions, experimental treatments and chemical analysis. Changes in NUE can be explained by a higher proportion of perennial ryegrass and genetic improvement.

Keywords: nitrogen fertiliser, nitrogen uptake, Soil Nitrogen Supply, Apparent Nitrogen Recovery, Nitrogen Use Efficiency, soil type, cutting frequency, grazing

Introduction

A large number of experiments on nitrogen (N) fertilisation of grassland have been carried out in the Netherlands in the last sixty years. From about 1935 until about 1970 the main objective was to increase herbage production. After 1970, there was an increasing concern about losses of N to the environment by nitrate leaching, ammonia volatilisation and denitrification, leading to a shift in research topics. Quantifying losses (e.g. Ryden, 1984; Bussink, 1994; Velthof, 1996) and developing management rules to reduce N losses (Korevaar & Den Boer, 1989; Wouters & Hassink, 1995; Peel *et al.*, 1997; Cuttle *et al.*, 1997) became the main objectives of the N research. Further research on N will emphasise the complexity of soil processes and the scaling of effects to reduce N-losses (Jarvis, 1996).

From the farmers point of view, improved N utilisation creates possibilities to reduce N inputs and losses without severe reductions in technical and financial results. Therefore a good knowledge about the effects of N fertilisation in relation to farm management is important.

In many fertilisation experiments the effect of single management factors (e.g. cutting frequency, grazing vs. cutting) on DM yield and N uptake have been analysed by using the three quadrant diagram (Frankena & De Wit, 1958; De Wit, 1953). For a good understanding of the differences in the response of herbage yield to fertiliser N the following aspects should be analysed in the three quadrant diagram (Van Der Meer & Van Uum-Van Lohuyzen, 1986):

- N supply from other sources than fertiliser, mostly measured on unfertilised plots. The most important source is the net mineralisation (Hassink, 1995), but N from precipitation and dry deposition and N supply by white clover and other N fixing organisms can contribute a substantial amount. This (combined) source is often called the Soil Nitrogen Supply (SNS);
- the extra N uptake in the harvested DM in relation to the amount of applied fertiliser N. This is calculated as *(N uptake – SNS) / N applied* and called the Apparent Nitrogen Recovery (ANR). The complement of the nitrogen recovery gives information about the nitrogen that might remain in the soil (organic and inorganic N) and in roots and stubble of the plants. Therefore knowledge about the nitrogen recovery is an important factor to detect and develop efficient grassland fertilisation and management systems;
- the DM production per kg of N uptake in the harvested DM, the Nitrogen Use Efficiency (NUE). This relationship defines the total DM yield and the N content of the herbage. Consequently, this partly defines the N losses by utilisation of the herbage by animals (Van Vuuren, 1993).

Brockman (1969), Brockman *et al.* (1971) and Richards & Hobson (1977) analysed relationships between soil N, fertiliser N and N-uptake in UK-experiments. Van Der Meer & Van Uum-Van Lohuyzen (1986) analysed the change in ANR over the last fifty years in Dutch fertilisation experiments. They concluded that ANR had increased strongly after 1970. Ruitenberg *et al.* (1991) developed a relationship between optimum N-application rates, SNS and ANR. These overviews give a useful characterisation of relationships between fertiliser input and N uptake.

For a complete understanding of the proces of fertilisation, N uptake and DM production, also the relationship between SNS, ANR and NUE must be analysed. Until now, such a combined analysis of SNS, ANR and NUE has not been made in a group of experiments.

During the last sixty years many fertilisation experiments have been carried out. In this paper the available data from these experiments have been analysed to characterise changes in SNS, ANR and NUE in relation to a number of management factors and to trace changes in time. Special attention has been paid to the effects of soil type, the application level of N, grazing versus cutting and the cutting frequency.

Materials and methods

The collected experiments

We collected data from N fertilisation experiments using calcium ammonium nitrate (CAN), carried out in the Netherlands in the period 1934–1994. Experiments and treatments without adequate application of P and K were excluded.

For all experiments several characteristics, if available, have been recorded:

- soil type: sand, clay, poorly drained and well drained peat;
- organic matter content or organic nitrogen content of the soil;
- white clover content on the unfertilised plot and on the fertilised plot;
- N content: Crude Protein (CP) or the total N (N_t)
- number of cuts per year
- utilisation, a mix of grazing and cutting or pure cutting
- other management factors: grassland renovation, cutting effect of slurry injection equipment

The number of experiments lasting one and two years is limited, there is a large group of long-term experiments, with a maximum time of 22 years. Permanent grassland was the basis for almost all the experiments. The exact history of all the experimental sites is unknown, but in general the experiments before 1970 were carried out on (very) old grassland (>10 years old). After 1970 relatively more experiments were carried out on renovated, but still permanent grassland. In the experiments of the research station for cattle husbandry, renovated grassland had to be older than 3 years to be used in fertiliser experiments. Grassland renovation as experimental treatment has been marked in the dataset.

In total a unique dataset of 4700 records has been made. (Annex 1)The data are spread over the whole period, with a peak in the period 1960–1975 (Figure 1). A total of 4400 records was available for N application rates in the range of 0–500 kg N per ha per year. About 300 records were present for application rates between 500 and 600 kg N per ha per year. Only 100 records with very high application rates (>

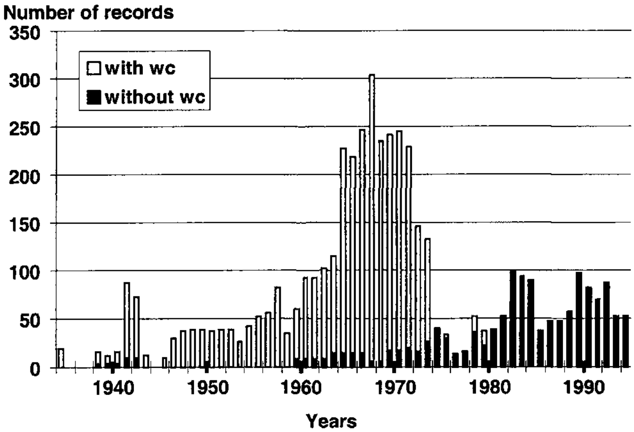

Figure 1. Frequency distribution of experimental records in the 'sixty-year' dataset of nitrogen fertiliser experiments over the periode 1934-1994. White parts are records with white clover, black parts are records without white clover.

700 kg N per ha per year) were present (Figure 2). Most of the records included white clover, also most of the records came from cutting experiments (Table 1). The average number of cuts was 5.3 with a variation between 2 and 10 cuts per year.

Well drained peat was excluded from the statistical analysis because half of the data came from a site where peat was recently covered with 6–18 cm of sand to improve bearing capacity. The other half of the data came from one site (Zegveld) and will be included in the results.

Statistical analysis

Models have been defined for both N uptake and DM yield. They consist of a fixed non linear submodel for the expected value and a random linear submodel for the deviation. First the fixed submodel was fit, using the maximum likelihood method

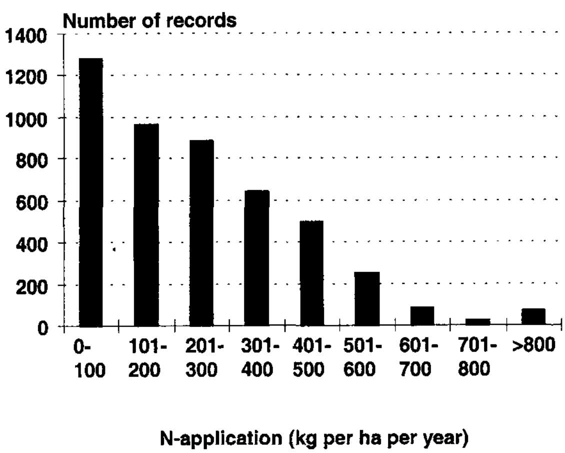

Figure 2. Number of records as a function of the level of fertiliser N application in the 'sixty-year' dataset of nitrogen fertiliser experiments.

Table 1. Records of the 'sixty-year' dataset of nitrogen fertiliser experiments sorted after soil type, the presence of white clover (wc), grassland use (grazing/cutting) and the average, minimum and maximum number of cuts.

Parameter	Soil type				
	Clay	Peat, well dr.	Peat, poorly dr.	Sand	Total
Without wc	417	164	237	587	1403
With wc	1436	5	752	1091	3284
Cutting	1679	90	889	1370	4028
Grazing	174	79	100	308	661
Cuts average	5.3	6.3	5.2	5.2	5.3
minimum	3	5	2	3	2
maximum	9	7	7	10	10
Total	1853	169	989	1678	4689

of Genstat with FITNONLINEAR. Only significant parameters were incorporated in the model ($P<0,05$). Secondly the submodel was fit for the deviations with the residual maximum likelihood method of Genstat using REML. We used Genstat 5, Release 4.1 (Anonymous, 1998).

The N uptake model, the fixed non linear submodel

For the expected value N_m we used a double Mitscherlich function (Equations 1and 2).

$$N_m = \alpha_0 + (\alpha_1 - \alpha_0) \,.\, [1 - \exp\{N_b / (\alpha_1 - \alpha_0)\}] \qquad (1)$$

Morrison et al. (1980) found a lower ANR at an application level of 150 kg N per ha, compared to 300 kg N per ha. Dowdell *et al.* (1980) and Dilz (1966, 1987) suggested the possibility of immobilisation of applied N in stubble, roots and microbial biomass, competing for N with harvestable herbage at low N soils. To test whether this would be the case in our dataset, we corrected the applied N for this possible immobilisation using a second Mitscherlich function:

$$N_b = N_g - \alpha_2 \cdot [1 - \exp(N_g / \alpha_2)\,] \qquad (2)$$

N_m = expected value of N uptake (kg/ha)
α_0 = N uptake when no N is applied, the SNS (kg/ha)
α_1 = maximum N uptake, realised at high levels of applied N (kg/ha)
α_2 = maximum immobilisation of applied N into stubble, root and microbial biomass. This immobilisation can be be temporarily or more permanent (kg/ha)
N_b = applied minus immobilisation, which is maximally α_2 (kg/ha)
N_g = N application rate (kg/ha)

The parameters α_0, α_1 and α_2 were related to soil type, the number of cuts, utilisation (grazing or cutting), soil organic matter, grassland renovation and white clover content (Equations 3 and 3a).We used an exponential function which can account for interactions between soil type, utilisation etc., It also has the advantage that all parameter estimates remain positive. Because we assumed that without soil organic matter the SNS (=α_0) would be nil, the α_0-function was slightly different from the others.

$$\alpha_0 = a_0 . [1-exp((om_0+om_{0S})OM)].exp[c_0C+s_0S+(g_0+g_{0S})G+(wc_0+wc_{0S})WC+r_0R] \quad (3)$$

$$\alpha_i = a_i . exp[(om_i + om_{iS})OM + c_iC+s_iS+(g_i+g_{iS})G+(wc_i+wc_{iS})WC+r_iR] \quad (3a)$$

i	= 1, 2 for the parameters α_1 and α_2,
om_0, om_i	= the coefficient for soil organic matter content,
om_{0S}, om_{iS}	= extra coefficient on soil type S for soil organic matter content
OM	= organic matter content of the soil (%),
s_0 , s_i	= coefficient for the effect of soil type, not related to the other factors,
S	= soil type, sand, clay or poorly drained peat.
c_0, c_i	= coefficient for the number of cuts
C	= number of cuts minus 5; 5 cuts is chosen as the reference value
g_0, g_i,	= coefficients for grazing/cutting
g_{0S}, g_{iS}	= extra coefficients for grazing/cutting on soil type S
G	= grazing/cutting, in case of cutting G = 0; in case of grazing G = 1
wc_0, wc_{0S}, wc_i, wc_{iS}	= coefficients for white clover
WC	= white clover as percentage dry weight on the unfertilised plot
r_0, r_i	= coefficient for grassland renovation
R	= grassland renovation with ploughing: no renovation = 0, renovation = 1

About three quarter of the data of N uptake were based on a crude protein analysis, using the Kjeldahl method. The remainder was based on a total N analysis. A correction for these different techniques was added (Equation 4):

$$N_c = N_m . exp(-\lambda_l N_m) \quad (4)$$

N_c = the corrected N uptake
N_m = the N uptake in the dataset
λ_l = correction for the N uptake when the Kjeldahl method was used.

The N uptake model, the random linear submodel.

The submodel for the deviations is shown in (Equation 5) and consists of stochastic, normal distributed terms for year and plot/site, their interactions and random effects.

$$Y_N = N_c + \varepsilon_Y + \varepsilon_P + \varepsilon_{YP} + \varepsilon_R \quad (5)$$

In which:
Y_N = the measured N uptake in the experiments (kg/ha)
N_c = the corrected N uptake (kg/ha)
ε_Y = deviation caused by year effects
ε_P = deviation caused by plot/site effects
ε_{YP} = deviation caused by interactions between year and plot/site effects
ε_R = deviation caused by random effects

The DM yield model, the fixed non linear submodel

The DM yield is expressed as a function of N uptake and is based on the assumption that initially the N content increases slowly as N application increases (Reid, 1970, 1972). At high N applications a linear relationship between N application and N content was assumed. Hence, (Equation 6):

$$N / DM = \beta_0 + \beta_1^{-1}[1-exp(-\rho N)]N \tag{6}$$

Transformation resulted in the following function(Equation 7):

$$DM = [\beta_0/N + \beta_1^{-1}(1-exp(-\rho N))]^{-1} \tag{7}$$

DM = the expected value of DM yield (kg/ha)
β_0 = minimum N content (kg / kg)
β_1 = maximum DM yield that can be realised at very high levels of N uptake (kg/ha)
ρ = defines the change over of the grass to luxury consumption (–)
N = the N uptake (kg/ha)

The parameters β_0, β_1 and ρ are related to soil type, number of cuts, utilisation (grazing or cutting), soil organic matter, grassland renovation and white clover content (see equations 8 and 9).

$$\beta_i = b_i.\ exp[(om_i + om_{iS})OM + c_iC+s_iS +(g_i+g_{iS})G+(wc_i+wc_{iS})WC+r_iR] \tag{8}$$

$$\rho = r.\ exp[(om_r + om_{rS})OM + c_rC+s_rS +(g_r+g_{rS})G+(wc_r+wc_{rS})WC+r_rR] \tag{9}$$

i = 1, 2 for the parameters β_1 and β_2,
r = for the parameters belonging to ρ
with S, C, G, OM, R, WC being the same as above.

To test whether the CP or N_t analysis affected the relationship between DM yield and N uptake we used the same Equation as is used in the N uptake model. Only the parameter λ_1 has been replaced by λ_2 (Equation 10):

$$N_c = N_m\ .\ exp(-\lambda_2\ N_m) \tag{10}$$

N_c = the corrected N uptake
N_m = the N uptake in the dataset
λ_2 = correction for the N uptake when the Kjeldahl method was used.

The DM yield model, the random linear submodel.

The model for the deviations is shown in Equation 11 and consists of stochastic, normal distributed terms for year and site.

$$Y_{\mathrm{DM}} = DM + \varepsilon_Y + \varepsilon_P + \varepsilon_{YP} + \varepsilon_R \qquad (11)$$

In which:
Y_{DM} = the measured DM yield in the experiments (kg/ha)
DM = the calculated DM yield (kg/ha)
Deviation terms are the same as in Equation 5.

Results

Firstly, the results of the statistical analysis will be discussed. Secondly, the relationship between N fertiliser application, DM yield, N uptake and ANR will be presented. Therefore the three quadrant diagram as developed by De Wit (1953) will be extended to a four-quadrant-diagram. Additional to the three quadrants with N application, N uptake and DM yield, the ANR has been calculated from the lines in the fourth quadrant (N uptake and N application) and shown separately in the third quadrant (below-left). To show the NUE in the diagram, dotted lines are placed in the first quadrant (above-right), (e.g. Figure 3).

N uptake model

The fixed model for N uptake accounted for 72.1% of the total variance (Table 2), for 36.4% of the total 'between-year' variation, for 64.9% of the 'between-site' variation and for 89.9% of the random and experimental (fertiliser level, grazing/cutting, cutting frequency, white clover) variation. The standard error of the observations was estimated to be 65.9 kg N per ha. Results of the random model for N uptake (Equation 5, Table 2) show that 18% of the total variation was caused by year and site effects, and 36% by year-site interactions. Random variation was still 27% of the total variation.

The values of the parameters are shown in Table 3. Values of a_0, a_1 and a_2 are in kg per ha. The other parameters are without dimension, positive values of these parameters indicate an increase of a_i, negative values a decrease.

The Soil Nitrogen Supply (α_0) was significantly affected by the soil organic matter, soil type, grassland use and, on sand, by the white clover content. The effect of soil organic matter on sand was significantly different from that on clay.

The maximum uptake level (α_1) was increased by grassland renovation and a high-

Table 2. Estimates of variance for the contribution of year, site, year by site interaction and random terms, the relative importance of the residual variance of the four components and the percentage of the total variance that is accounted for by the N uptake model.

N uptake model			
Component	Estimate of variance (kg/ha)	Relative importance of total variance (%)	Percentage of total variance accounted by the model (%)
σ^2_{year}	795	18.3	36.4
σ^2_{site}	801	18.5	64.9
$\sigma^2_{year\ by\ site}$	1571	36.2	–
σ^2_{random}	1173	27.0	89.9
σ^2_{total}	4340	100.0	72.1

Table 3. Parameter values of the model for N uptake based on the analysis of the 'sixty-year' dataset of nitrogen fertiliser experiments.

N uptake model	Estimate	s.e.
Soil Nitrogen Supply (α_0, kg/ha)		
a_0	192.45	2.87
$s_{0,peat}$	0.2691	0.0163
om_0	0.984	0.224
$om_{0,sand}$	–0.735	0.224
g_0	0.1335	0.0228
$wc_{0,sand}$	0.00364	0.00121
Maximum N uptake(α_1, kg/ha)		
a_1	696.2	17.6
om_1	–0.004944	0.000934
g_1	–0.4217	0.0569
$g_{1,peat}$	0.2324	0.0774
r_1	0.2017	0.0886
c_1	0.1407	0.0103
Immobilisation(α_2, kg/ha)		
a_2	51.42	5.49
wc_2	0.04050	0.00473
r_2	0.661	0.105
Chemical analysis (λ_1, –)		
λ_1	0.0000445	0.0000195

er cutting frequency. The maximum uptake level was sharply decreased by grazing instead of cutting, although the effect was less strong on peat. Increasing organic matter contents also reduced the maximum uptake level.

The immobilisation of applied N (α_2) was significantly affected by grassland renovation and the white clover content.

Measuring N uptake by CP analysis gave a significantly lower uptake than measuring by the N_t analysis.

DM yield model

The fixed model for DM yield accounted for 87.0% of the total variation, with a standard error of 999 kg. Of the total between year variation, almost 70% was accounted for by the fixed part of the model, for the between site variation this was 83% and for the variation not related to year or site (fertiliser level, grazing/cutting, cutting frequency, white clover) this was 92% (Table 4). Results of the random model (Equation 10, Table 4) show that only 20–22% of the total variation was caused by year and site effects, the variation caused by year-site interactions was only 13.4%. Variation not related to year or site was 44.3% of the total variation.
The values of the parameters are shown in Table 5.

The minimum N content (β_0) was significantly different for the three soil types. The minimum N content was significantly increased by a higher cutting frequency, grassland renovation and grazing, the effect of grazing was stronger than from the other two factors.

The maximum DM yield at very high levels of N uptake (β_1) was on clay significantly higher than on sand and peat, indicating lower N contents on clay. The value also was increased by grazing, grassland renovation and cutting frequency. The effect of cutting frequency was also sigificant, but smaller in comparison to the other factors. The white clover content had no effect on the parameter.

The change over to luxury consumption (ρ) was on clay significantly lower than on peat and sand. The ρ was significantly increased by a higher cutting frequency and white clover. The effect of white clover was much smaller than the effect of cutting frequency. There was almost a linear increase of the N content at increasing uptake levels. Only at very low uptake levels on clay soil a slower increase in N content was found.

There was a sigificant effect of the way the N uptake was analysed. The value of λ_2 was negative, but in combination with the minus sign, the result was positive. This means that the NUE was lower in case of a CP analysis, compared to an N_t analysis.

Table 4. Estimates of variance for the contribution of year, site, year by site interaction and random terms, the relative importance of the residual variance of the four components and the percentage of the total variance that is accounted for by the DM yield model.

DM yield model			
Component	Estimate of variance (kg/ha)	Relative importance of total variance (%)	Percentage of total variance accounted by the model (%)
σ^2_{year}	204113	20.5	69.6
σ^2_{site}	217447	21.8	83.1
$\sigma^2_{year\ by\ site}$	134028	13.4	37.1
σ^2_{random}	441704	44.3	92.0
σ^2_{total}	997292	100.0	87.0

Table 5. Parameter values of the model for DM yield based on the analysis of the 'sixty-year' dataset of nitrogen fertiliser experiments

DM yield model	Estimate	s.e.
minimum N content (β_0, kg/kg)		
b_o	0.018750	0.000233
c_0	0.04143	0.00735
r_0	0.0977	0.0163
g_0	0.1875	0.0211
$s_{0,peat}$	–0.0926	0.0202
$s_{0,sand}$	–0.2108	0.0166
maximum DM yield(β_1, kg/ha)		
b_1	31418	583
c_1	0.0342	0.0106
r_1	0.2803	0.0324
g_1	0.2295	0.0485
$s_{1,peat}$	–0.0860	0.0288
$s_{1,sand}$	–0.2141	0.0230
Speed of luxury consumption(ρ,–)		
r	0.006400	0.000481
c_r	1.218	0.107
wc_r	0.0871	0.0111
$s_{r,peat}$	3.794	0.470
$s_{r,sand}$	2.862	0.426
Chemical analysis (λ_2, –)		
λ_2	–0.0001496	0.0000168

Effect of soil type

The mean SNS on poorly drained peat soils was 252 kg N per ha. On sand and clay, SNS was 176 and 192 kg N per ha, respectively (Figure 3). In the dataset the average OM content in the top soil (0–5 cm) on peat soils was 45%, on sand and clay this was 10 and 20%, respectively. The SNS on sand decreased in the years after 1970, due to a decrease in soil organic matter (Figure 4). This decrease in SNS was not seen on clay, despite the decrease in soil organic matter (Figure 4).

Drainage of peat soils led in the first years to a strong increase in SNS (Boxem & Leusink, 1981). However, experiments twenty years later on the same site did not show a higher SNS on the drained peat soil (Hofstede *et al.*, 1995; Hofstede, 1995a, 1995b)

The mean ANR on poorly drained peat soils was 7 to 10% lower than on sand and clay at N application levels higher than 200 kg N per ha (Figure 3). On well drained peat soils the ANR was much lower than on poorly drained peat, caused by a very high SNS. In the later experiments, with the same SNS on well and poorly drained peat soil, also no difference in ANR was found. Differences in mean ANR between sandy soils and clay soils were small.

At low levels of N uptake the mean NUE on sand was 0.7 kg DM per kg N uptake higher than on clay and poorly drained peat (not to be seen in Figure 3). At high up-

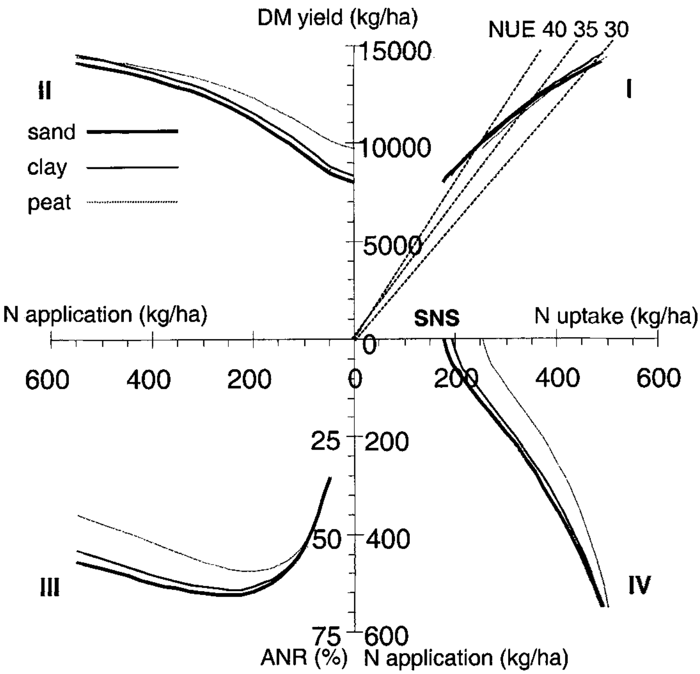

Figure 3. Mean effects of N fertiliser application on N uptake (quadrant IV), DM yield (quadrant II), ANR (quadrant III) and NUE (quadrant I) as a function of soil type (sand, clay and peat). Mean relationships are based on the whole 'sixty-year' dataset of nitrogen fertiliser experiments.

take levels (400–500 kg N) the mean NUE on clay was 0.5 to 1.0 kg DM per kg N higher than on sand.

Effect of fertiliser level

At low N application levels, the N uptake increased slowly and the mean ANR was low (Figure 3, quadrant III), e.g., with 50 kg N per ha the ANR on sand was 35%. Increasing N application to 200 kg per ha led to a stronger increase in N uptake (quadrant IV) and mean ANR increased to a maximum level of 65–70% (quadrant III). Higher N applications led to a slower increase in N uptake and a decreasing ANR. At 550 kg N per ha the mean ANR was 55–60%.

The maximum N uptake level was not presented in Figure 3, but was 660, 630 and 560 kg N per ha for sand, clay and peat, respectively. These asymptotic values are realised at N applications of more than 1000 kg N per ha.

Mean NUE decreased at increasing levels of N uptake. At an N uptake of 200 kg per ha, the mean NUE was 43 kg DM per kg N, whereas at about 490 kg N per ha (the maximum N uptake in Figure 3), the mean NUE was 29 kg DM per kg N. At the maximum N uptake level of the uptake model the mean NUE was 24.2, 26.0 and 27.4 kg DM per kg N for sand, clay and peat respectively, with five cuts per year.

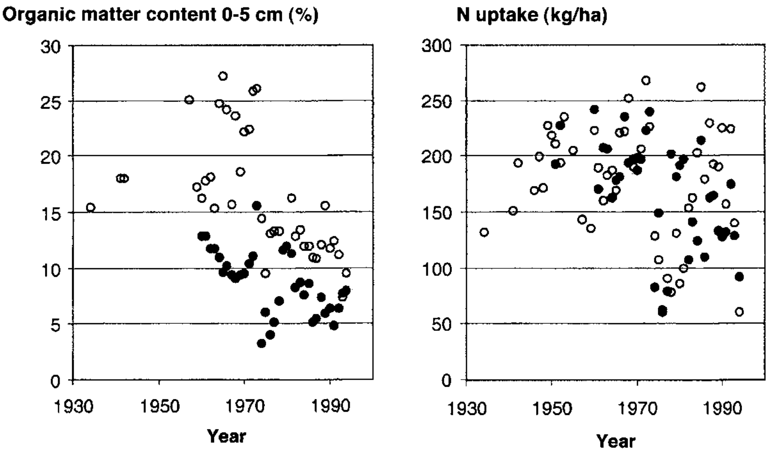

Figure 4. The soil organic matter content in the layer 0 to 5 cm and the N uptake on the unfertilised plots on the experimental sites in the 'sixty-year' dataset of nitrogen fertiliser experiments. (Open dots = clay, closed dots = sand).

Comparison between grazing and cutting

SNS was increased by a mixed use of grazing and cutting with 27 kg N per ha on sand and clay compared with only cutting. On peat the SNS increased with 40 kg N per ha. The maximum N uptake was decreased with about 200 kg N per ha on sand and clay and with about 100 kg N per ha on peat.

The increase in SNS and the decrease in maximum N uptake led to a lower ANR with grazing (Figure 5). This effect became stronger with increasing N levels. At 200 kg N per ha, the difference in ANR was 5%, at 500 kg N per ha the difference increased to 10%.

Grazing resulted in a decrease in NUE of 2 kg DM per kg N uptake at levels of 200–300 kg N uptake (Figure 5). These differences decreased at increasing N levels.

Effect of cutting frequency

The mean SNS was not affected by cutting frequency. The maximum N uptake level was higher with an increased cutting frequency. N uptake levels on sand with 3, 5 and 8 cuts per year with an N application of 550 kg per ha, were 430, 490 and 550 kg N per ha, respectively. The higher maximum N uptake level led to a higher ANR by frequent cutting. This increase in ANR was stronger at higher application levels (Figure 6). An increased cutting frequency from 3 to 8 cuts at application levels of 200 and 400 kg N per ha per year led to an increase in ANR of 8 and 18 units respectively. The mean NUE was decreased by frequent cutting. Increasing the cutting frequency from 3 to 8 cuts per year led to a decrease in NUE of 3 to 4 units. The DM yield is a result of the ANR and the NUE, according to equation 12:

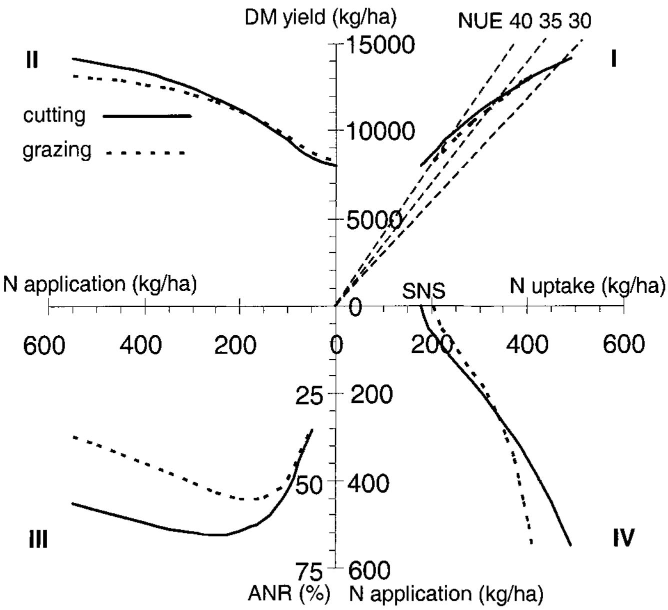

Figure 5. Mean effects of N fertiliser application on N uptake (quadrant IV), DM yield (quadrant II), ANR (quadrant III) and NUE (quadrant I) under pure cutting and mixed grazing/cutting conditions on sand. Mean relationships are based on the whole 'sixty-year' dataset of nitrogen fertiliser experiments.

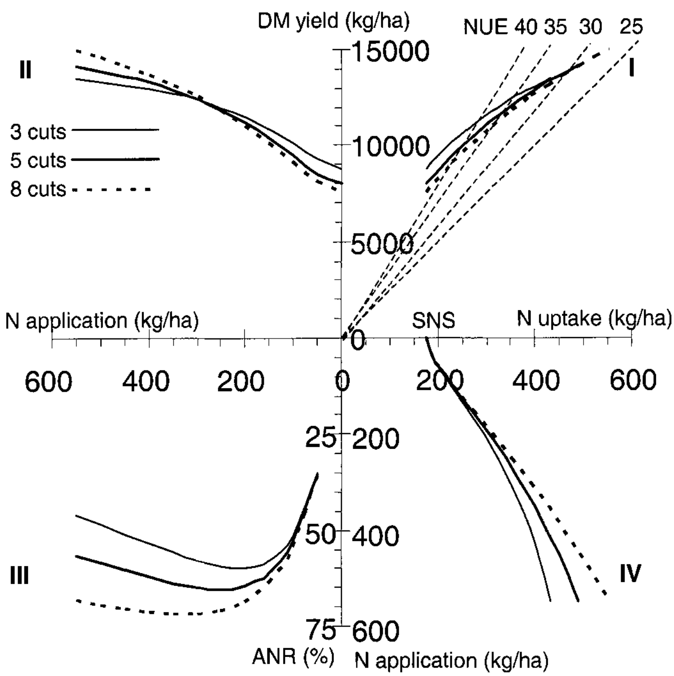

Figure 6. Mean effects of N fertiliser application on N uptake (quadrant IV), DM yield (quadrant II), ANR (quadrant III) and NUE (quadrant I) at 3, 5 and 8 cuts per year on sand. Mean relationships are based on the whole 'sixty-year' dataset of nitrogen fertiliser experiments.

$$DM = NUE_{Nuptake} \, x \, (SNS + ANR_{Napplied} \, x \, N_{applied}) \quad (12)$$

In this equation the strong increase in ANR at an application level of 400 kg N per ha was enough to compensate the decrease in NUE and the DM yield was higher with 8 cuts, compared to 3 cuts per year.

Effect of CP/Nt analysis

At N application levels of 200 and 400 kg N per ha, the N uptake was 319 and 433 kg per ha, respectively. At those uptake levels, the difference in calculated N uptake between the CP and the N_t analysis was 4.5 and 8 kg per ha, respectively. Related to this, the ANR was underestimated by 1.5 to 2% by using the CP analysis instead of the N_t analysis (Table 6).

When N uptake was measured as CP, the DM yield, and with it, the NUE was lower than with the same N uptake based on the N_t analysis. The difference between both methods was about 0.90 kg DM per kg N uptake (Table 6).

Discussion

Soil type

On peat soils SNS was much higher than on clay and sand. The strong increase in SNS short after the improved drainage (Boxem & Leusink, 1981) could not be repeated in later experiments in 1992–1994 (Hofstede *et al.*, 1995; Hofstede 1995a, 1995b). The reason for this is not clear, the physical changes in peat soil by drainage might play a role (Schothorst, 1982).

The SNS on clay was about 15 kg N per ha higher than on sand. This difference was related to a higher organic matter content on clay than on sand. The N uptake model showed a faster increase in mean SNS related to soil OM on clay than on sand. Due to the lack of experiments with low organic matter contents on clay in our dataset it is likely that no good relationship on this soil type could be established. The results from other datasets are confusing. Hassink (1995) found at similar levels of soil organic matter a lower SNS on clay soils than on sandy soils. In contrast, Herlihy & McAleese (1978) found a higher SNS on loam, compared to sandy loam. On

Table 6. The ANR at three levels of N application and the NUE at three levels of N uptake, with the N uptake based on the CP analysis and the N_t analysis. Analysis based on the 'sixty-year' dataset of fertiliser experiments.

N application	ANR (%)		N uptake	NUE (kg/kg)	
(kg N per ha)	CP-analysis	N_t analysis	(kg N per ha)	CP-analysis	N_t analysis
200	63.0	64.5	200	42.5	43.3
400	60.5	62.3	400	31.4	32.3
600	53.2	54.8	600	24.8	25.7

the other hand, Whitehead (1984) did not find any relationship between the proportion of availabe soil N and the content of organic matter.

The mean ANR on sandy soils in our dataset was slightly higher than on clay soils. This is in agreement with the findings of Herlihy & McAleese (1978). They found ANR values of 59, 57 and 54% for sandy loam, coarse sandy loam and loam, respectively. In contrast, Whitehead (1984) could not find any relationship between apparent recovery and soil characteristics like contents of sand, clay, silt and organic matter.

Fertiliser level

In agreement with our results, low levels of ANR at low application levels have also been found by Herlihy *et al.* (1978) and Morrison *et al.* (1980). Dilz (1966, 1987) stated that there is a substantial N buffering in stubble and roots, which might cause low ANR's at low fertiliser levels. Although Dilz(1966, 1987) and Dowdell *et al.* (1980) stated that this immobilisation might occur at low N swards, we found this as an overall effect on swards with low to high levels of SNS. Also Reid (1970, 1972) found the same course of ANR as in our model, by using a four parameter function for N uptake.

Fertilisation might affect the SNS by a priming effect (Dowdell *et al.*, 1980; Dawson & Ryden, 1985), pool substitution (Rao et al., 1992) or by increased root growth (Whitehead, 1984). A priming effect by fertilisation would increase the calculated ANR, already at low application levels, which is in contrast with the results of our model.

ANR decreased with increasing applications over 200 – 250 kg N per ha. This has also been reported by Bartholomew & Chestnutt (1977) and Morrison *et al.* (1980) Richards & Hobson (1977) fitted a quadratic curve which implies a decreasing ANR over the whole range of fertiliser levels.

When instead of the cumulative ANR, based on the unfertilised plot: ($Nuptake_A - Nuptake_0)/(N_A - N_0)$), the marginal ANR (($Nuptake_A - Nuptake_{A-1}) / (N_A - N_{A-1})$) is calculated, the increase and subsequent decrease of ANR with increasing application levels are much stronger (Figure 7). The maximum marginal ANR of 78%was reached at about 100 kg N per ha. At that application level, the immobilisation of N (the A_2 in the model)was almost maximal. This suggests that the competition for N between microbial biomass, roots and stubble ends when more than 100 kg N per ha is applied.

In agreement with our results, a decreasing NUE (or an increasing N content) at increasing levels of N uptake has been seen many times (e.g. Reid, 1970, 1972; Morrison *et al.*, 1980; Harkess & Frame, 1986; Hopkins *et al.*, 1990). However at low application levels (between 0 and 100 kg N per ha) and low levels of SNS a constant or even increasing NUE has been found (Reid, 1970, 1972). We also found this effect in our model on clay soils at low N uptake levels(< 100 kg N per ha).

The increase in ANR at low application levels and the relatively slow decrease in NUE indicate that a minimum application level of at least 100 kg N per ha is required to realise a good N utilisation. This means that on a farm with low N input

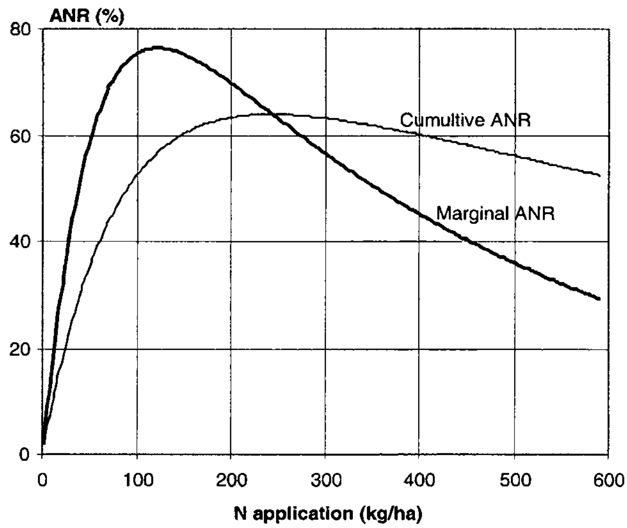

Figure 7. The course of the cumulative (related to the unfertilised plot) and the marginal ANR (related to the last kg of applied N) in relation to N application on sand. Data based on the 'sixty-year' dataset of fertiliser experiments.

levels, it might be more efficient to fertilise only half of the paddocks with 100 kg N per ha instead of applying 50 kg N per ha on all the paddocks.

Comparison of grazing and cutting

SNS was increased by a mixed use of grazing and cutting. This was confirmed by Prins & Brak (1984) and Thomas *et al.* (1990). Beside the the return of excreta, increased tiller numbers on grazed plots might increase exploitation of soil N, leading to a higher SNS (Thomas *et al.*, 1990).

In agreement to our results, a decreased ANR has been found by Jackson & Williams (1979), Prins & Brak (1984) and Deenen (1994). However, there are differences in the decline of the ANR by grazing between the different authors.

Prins & Brak (1984) found a stronger reduction in ANR in individual cuts on only grazed plots compared to plots with a mixed use of grazing and cutting. Differences between pure cutting plots and mixed use plots were relatively small. The grazing trials in our dataset had a mixed use with one or two cuts for silage, to realise a common use in the Netherlands. The strong decrease in ANR, as found by Jackson & Williams (1979) and Deenen (1994) might be related to the strong negative effects of pure grazing on sward quality, caused also by winter damage, poaching and urine scorch. The negative effect of urine scorch has also been mentioned by Prins & Brak (1984). Model calculations showed that urine scorch was the most important factor in decreasing herbage response to fertiliser N (Mooij & Vellinga, 1993). Also the very high ANR on the cutting plots in the experiments of Deenen (1994) might enhance the difference between grazing and cutting.

Grazing also led to an decrease in NUE (Figure 5), at low N application levels. This was confirmed by Prins & Brak (1984), who found similar effects for pure grazing and mixed use. Data from Deenen (1994) showed that the poor sward quality (i.e. an open sward) also resulted in a stronger reduction in NUE than was found in our model and by Prins & Brak (1984). This effect of a low NUE at open swards was also found in pot experiments by Van Loo *et al.* (1993).

Fertiliser recommendations for grazing and cutting have been discussed intensively. No difference in recommendations was made for grazing and cutting, except for the target yield (Mooij & Vellinga, 1993). However, the calculated optimal N application level was about 40 kg N lower for grazing, based on data in the United Kingdom and the Netherlands (Unwin & Vellinga, 1994). Deenen (1994) stated that the optimal application level for grazing was lower than 250 kg N per ha, a difference of about 150 kg N with the optimal application level for cutting. The optimal N application levels for cutting and grazing at the same cutting frequency in our analysis were 410 and 320 kg N, respectively. This difference between grazing and cutting is thus stronger than was stated by Mooij & Vellinga (1993) and Unwin & Vellinga (1994), but fits well with the new fertiliser recommendations (Vellinga, 1998).

It is concluded from our model and the literature that the negative effects of grazing are much stronger under pure grazing than with a mixed use of grazing and cutting. This implies that a mixed use of grazing and cutting should be recommended in practice.

Cutting frequency

In our dataset cutting frequency had no effect on SNS (Figure 6). This was also found by Holliday & Wilman (1965), Frame (1973), Reid (1978) and Kirkham & Wilkins (1994). In contrast, Bartholomew & Chestnutt (1977) found an increasing SNS (from 104 to 151 kg N per ha) with decreasing cutting frequency (from 10 to 3 cuts per season). However, a decreased cutting frequency by a delay of the first cut from half May to the half of June resulted in a decrease in SNS of about 20 kg N on average (Korevaar, 1986). When there were only two cuts per year, the SNS decreased even more (Holliday & Wilman, 1965; Bartholomew & Chestnutt, 1977).

ANR increased strongly with more frequent cutting. This was also found by Bartholomew & Chestnutt (1977), Reid (1978) and Kirkham & Wilkins (1994). In contrast, Holliday & Wilman (1965) and Frame (1973) did not find an effect of changes in the cutting frequency on ANR. This was possibly related to their lower maximum N levels and the presence of white clover.

More frequent cutting always led to a decrease in NUE (Figure 6). This was confirmed by Holliday & Wilman (1965), Frame (1973), Bartholomew & Chestnutt (1977), Reid (1978) and Kirkham & Wilkins (1994).

In addition to this, a large delay of the first cut, at the same number of cuts during the whole season, led to an increased NUE (Kreil & Kaltofen, 1966; Kirkham & Wilkins, 1994). The increase in NUE over the whole year was less than for the first cut, since the later cuts were cut at a younger stage and tended to have a higher N content.

Cumulative effects

The analysis of the data on an annual basis shows the importance of good grassland management in terms of a combination of grazing and cutting and the cutting frequency. Also practical conclusions may be drawn from this analysis. But analysing N uptake and DM yield per year,was still an analysis of cumulative effects. The N uptake and DM yield per year are the result of applying N per cut and harvesting per cut. To improve our understanding of the effects and interactions of application level, grassland use and cutting frequency better, results should be analysed per cut. For a single cut the relationships between growth period, SNS, ANR and NUE are more clear than for a complete growing season. Residual effects of individual cuts can be large, heavy cuts leading to regrowth retardation (DeWit, 1987), heavy applications to considerable residual N effects (Prins, 1983). Fertiliser experiments with successive harvests in individual cuts and special attention to the pretreatment (N application, yield of the previous cut) provide the right data for such an analysis (Prins *et al.*, 1980; Wieling & De Wit, 1987).

Development over time

A dataset of such a long period invites to analyse changes over time. Such an analysis must be done very carefully. There is a large variation in weather conditions and the dataset is not balanced. The records are not even spread over the whole period. Cutting and drying techniques have changed. In some of the oldest experiments yields were expressed in kg hay, which was assumed as having a dry matter content of 88%. Cutting height was always kept constant in an experiment with one or more sites. But between experiments there might have been some differences in cutting height. The effect of a variation in cutting height was expected to be small (Del Pozo Ibanez, 1963).

Grassland renovation, drainage, soil fertility, grassland management and other factors are confounded with time. Since about 1970 remarkable changes in experimental conditions took place. After 1970 the average number of cuts increased from

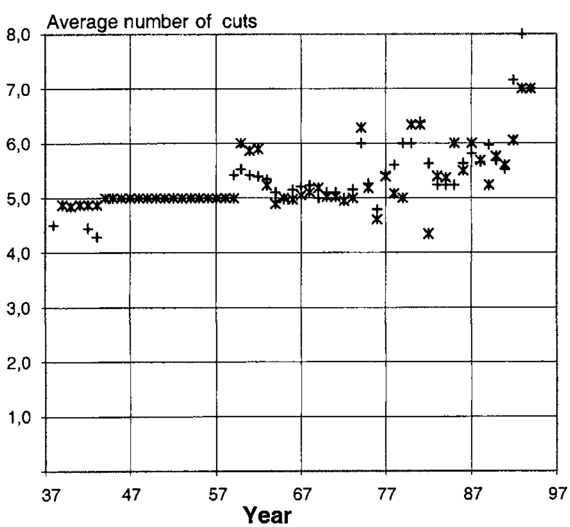

Figure 8. The average number of cuts per year in the fertilisation experiments in The Netherlands. (+ = sand, * = clay).

five to about six cuts per year (Figure 8). Despite the increased cutting frequency, in most of the treatments cutting was still carried out according to date. Before 1970, white clover was present in most of the experiments (Figure 1). Furthermore, relatively many fertilisation experiments took place with grazing. Since 1973 SNS of experimental sites on sand was lower than before, due to the lower content of soil organic matter (as a result of ploughing) and the larger share of young grassland(Figure 4). Since 1970 also the technique to measure N uptake has changed from the CP analysis to the N_t analysis (Table 6).

Van Der Meer & Van Uum-Van Lohuyzen (1986) reported an increase in ANR after 1970, possibly caused by improved drainage and improved grassland management and the absence of clover in unfertilised plots. The dataset of Van Der Meer & Van Uum Van Lohuyzen (1986) contained many data from peat soils before 1970, but only a few after 1970. After corrections are made for soil type and the change in experimental conditions since 1970 (grazing/cutting, cutting frequency, white clover (Frame, 1973), grassland renovation and chemical analysis of N uptake), an increase in ANR in time has not been found.

The change from the CP analysis to the N_t analysis around 1970 also affected NUE (Table 6). The N_t measurement had a higher NUE of about 1 kg DM per kg N, compared to the CP measurement. This sounds surprising, because the opposite effect would be expected. In an N_t analysis, also nitrate was included, but nitrate has not contributed to the formation of dry matter, so its NUE is nil. Grassland renovation led to a larger share of perennial ryegrass and the the latest varieties were sown. Harkess & Frame (1986), Sheldrick *et al.* (1986) and Frame (1991) clearly showed the superior NUE of perennial ryegrass in relation to other species. Van Loo *et al.* (1992), Vellinga & Van Loo (1994) and Baan Hofman (1988) showed that genetic improvement towards persistency and higher growth rates lead to a higher NUE. Data from Hopkins *et al.* (1990, 1995) also show a higher NUE on reseeded grasland, compared to old swards.

This increase in NUE might be small, only 1 kg DM per kg N. But the NUE plays a very important role in the DM production, as shown by equation 12.

In our dataset the mean SNS on mineral soils was about 180 kg N, the mean ANR at a fertilisation level of 200 kg N per ha was 65% and the total N uptake was 310 kg per ha. At that level of N uptake the mean NUE was 34 kg DM per kg N. Changes in SNS, ANR and NUE of 1 kg N, 1% and 1 kg DM per kg N uptake result in changes in DM yield of 34, 68 and 310 kg per ha, respectively.

In conclusion, changes in ANR over time could be explained by soil type, sward age (and soil organic matter content), grassland use, cutting frequency, white clover and chemical analysis of N uptake. Changes in NUE over time are due to the increase and genetic improvement of perennial ryegrass.

Conclusions

Analysis of a dataset of many years of fertilisation experiments led to a confirmation of well known results, but also to some new results:

- The increasing ANR and the slowly decreasing NUE at low N application levels indicate the necessity of a minimum application of at least 100 kg N per ha to realise a good N utilisation.
- Grazing leads to a higher SNS, a lower ANR and NUE, compared to cutting. These effects are stronger with pure grazing than with a mixed use of grazing and cutting.
- Changes in SNS on clay soil over time have not been found, a decrease in SNS on sand in the years after 1970 could be explained by a decrease in soil organic matter content.
- Changes in the ANR in fertiliser experiments over the last sixty years can be fully explained by changes in experimental conditions (soil type, sward age, organic matter content, white clover), experimental treatments (grazing/cutting, cutting frequency) and chemical analysis (N_t instead of CP).
- Changes in the NUE in fertiliser experiments over the last sixty years can be explained by the genetic improvement and the higher proportion of perennial ryegrass.

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Annex 1. Overview of used fertiliser experiments for the analysis of SNS, ANR and NUE.

Experiment	Source	Soil type	Years	Records
Pr149	Frankena(1939)	Poorly drained peat	1934	10
Pr154	Frankena(1939)	Clay	1934	10
Pr458	Frankena(1945)	Sand	1938-1942	20
CI15	Bosch *et al.* (1963)	Sand	1938-1960	221
CI16	Frankena(1945)	Poorly drained peat	1941-1942	8
CI18	Frankena(1945)	Clay	1941-1942	4
Pr640	Mulder(1949)	Poorly drained peat	1941-1942	58
Pr641	Mulder(1949)	Clay	1941-1942	58
CI203	Van Der Meer (pers. comm)	Clay	1946-1963	228
CI203	Van Der Meer (pers. comm)	Poorly drained peat	1946-1963	178
CI203	Van Der Meer (pers. comm)	Sand	1946-1963	68
CI1300b	Minderhoud(1960)	Poorly drained peat	1954-1957	15
CI1300	Minderhoud(1960)	Clay	1956-1957	65
CI1812	Hoogerkamp(1973)	Clay	1956-1962	48
PAW169	Hoogerkamp(1973)	Clay	1959-1964,1967	112
PAW246	Krist(1965), unpublished data	Well drained peat	1959-1966	72
PAW479	Mooij & Vellinga (1993)	Clay	1960-1971	84
PAW480	Mooij & Vellinga (1993)	Sand	1960-1971	84
PAW481	Mooij & Vellinga (1993)	Poorly drained peat	1960-1971	84
PAW642	Mooij & Vellinga (1993)	Clay	1962-1971	70
PAW643	Mooij & Vellinga (1993)	Sand	1962-1971	70
PAW644	Mooij & Vellinga (1993)	Poorly drained peat	1962-1971	70
PAW667	Woldring (1975a)	Clay	1963-1972	160
PAW803	Krist (1972)/Woldring (1975c)	Sand	1963-1973	66
PAW970	Van Der Meer (pers. comm)	Clay	1964-1973	504
PAW970	Van Der Meer (pers. comm)	Poorly drained peat	1964-1973	342
PAW970	Van Der Meer (pers. comm)	Sand	1964-1973	486
PAW764	Hoogerkamp(1973)	Sand	1965-1967	24
PAW1120	Woldring (1974)	Sand	1966-1970	90
ALG97	Hoogerkamp(1973)	Clay	1966-1971	54
ALG119	Hoogerkamp(1973)	Clay	1967	45
IBS1162	Ennik(1972)	Clay	1969	12
PAW1682	Woldring (1975b)	Sand	1970-1973	12
Pr11	Boxem & Leusink(1981)	Well drained peat	1970-1975	36
Pr11	Boxem & Leusink(1981)	Poorly drained peat	1970-1975	36
IB2032	Prins & Van Burg (1979)	Clay	1973	8
IB2145	Prins *et al.* (1981)	Clay	1974	21
IB2146	Prins (1983)	Sand	1974-1978	30
PR416	Woldring (1977)	Sand	1975	4
IB2244	Prins (1983)	Clay	1975-1978	19
IB2259	Prins (1983)	Clay	1975-1978	22
PR577	Unpublished data	Sand	1978	12
PR700	Snijders *et al.*(1987)	Sand	1978-1981	32
PR652	Unpublished data	Sand	1979	16
PR653	Unpublished data	Sand	1979	16
CABO314	Van Der Meer (pers. comm.)	Clay	1979-1982	24
PR804	Snijders *et al.*(1987)	Sand	1979-1983	40
PR844	Snijders *et al.*(1987)	Sand	1980-1984	40
PR891	Korevaar (1986)/unpublished data	Poorly drained peat	1980-1988	81
PR965	Snijders *et al.*(1987)	Clay	1981-1983	12
ZV30	Korevaar (1986)/unpublished data	Poorly drained peat	1981-1988	72

Annex 1. Continued.

Experiment	Source	Soil type	Years	Records
CABO	BaanHofman(1988)	Sand	1982-1984	96
PR49	Wouters *et al.*(1995)	Sand	1982-1984	36
BZ25	Korevaar (1986)/unpublished data	Clay	1982-1991	144
PR228	Schils(1992)	Sand	1984-1985	8
PR229	Schils(1992)	Clay	1984-1985	8
IB3079	NMI, unpublished data	Clay	1986	5
PR386	Schils(1992)	Sand	1986-1988	12
PR387	Schils(1992)	Clay	1986-1988	12
PR388	Schils(1992)	Sand	1986-1988	12
IB3133	NMI, unpublished data	Clay	1987	5
IB3182	NMI, unpublished data	Sand	1988	5
IB3184	NMI, unpublished data	Clay	1988	5
IB3230	NMI, unpublished data	Sand	1989-1990	16
PR1536	Schreuder *et al.* (1995)	Sand	1989-1991	28
PR2531	Schreuder *et al.* (1995)	Clay	1989-1991	28
PRCd	Snijders *et al.* (1994)	Sand	1989-1992	48
PR1535	Schreuder *et al.* (1995)	Sand	1989-1991	16
PR4533	Schreuder *et al.* (1995)	Clay	1989-1991	16
PR5533	Schreuder *et al.* (1995)	Well drained peat	1989-1991	16
PRBZ	Schils *et al.* (1998)	Sand	1990-1992	30
PRWbh	Schils *et al.* (1998)	Clay	1990-1992	30
PR1578	Hofstede *et al.*(1995)			
	Hofstede (1995a,b)	Sand	1992-1994	40
PR3044	Hofstede *et al.*(1995)			
	Hofstede (1995a,b)	Clay	1992-1994	40
PR5562	Hofstede *et al.*(1995)			
	Hofstede (1995a,b)	Poorly drained peat	1992-1994	40
PR5563	Hofstede *et al.*(1995)			
	Hofstede (1995a,b)	Well drained peat	1992-1994	40
Total				4689