Effects of cutting or grazing grass swards on herbage yield, nitrogen uptake and residual soil nitrate at different levels of N fertilization

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Abstract

On a Flemish sandy loam soil, cut and grazed swards were compared at different levels of mineral nitrogen (N) fertilization. Economically optimal N fertilization rates were 400 (or more) and 200 kg N ha^{-1} yr^{-1} on cut and grazed swards respectively. Considering the amounts of residual soil nitrate-N in autumn, these N rates also met the current Flemish legal provisions, i.e. no more than 90 kg ha^{-1} nitrate-N present in the 0–90 cm soil layer, measured between 1 October and 15 November. The N use efficiency was considerably higher in cut grassland systems than in grazed systems, even when the animal component of a cut and conservation system was included. The results indicate that, for cut grasslands, two N application rates should be considered: intensively managed grasslands with high amounts of N (400 kg ha^{-1} yr^{-1} or more) or extensively managed grasslands with white clover and no more than 100 kg N ha^{-1} yr^{-1}.

Keywords: N use efficiency, nitrate leaching, white clover, mowing, grassland management, nitrogen fertilizer

Introduction

In past decades the yield response of grasslands to nitrogen (N) fertilization has been frequently studied. Due to the difficulty of measuring herbage yield in grazed swards, most of the research was conducted in cutting experiments and there is still a dearth of N-fertilizer rate experiments conducted under grazing (Frame *et al.*, 1998).

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Marginal yield response was used to determine the economically optimal rate of N application (Behaeghe and Carlier, 1973; Morrison, 1980; Neeteson and Wadman, 1987). The rate of N application that coincides with this economic yield response optimum might be excessive in terms of the potential for N losses to the environment (Hopkins, 2000).

More recently, environmental concerns have dominated and much research has focused on the losses of nutrients, in particular N, from intensively managed grassland systems. It is now known that significant amounts of N may be lost from grasslands by ammonia volatilization (Jarvis *et al.*, 1989; Jarvis, 1990; Scholefield *et al.*, 1991; Bussink, 1992, 1994; Watson *et al.*, 1992), by denitrification (Ryden, 1983; Jordan, 1989; Scholefield *et al.*, 1991; Watson *et al.*, 1992; Vermoesen, 1999) and by nitrate leaching. In view of the European concern for excessive amounts of leached nitrate in groundwater (Anonymous, 1991), numerous studies have been carried out to determine the ecological optimum for grassland N fertilizer rate. Figure 1 summarizes results from 19 studies dealing with nitrate leaching from grassland soils (Dowdell and Webster, 1980; Dowdell *et al.*, 1980; Garwood *et al.*, 1980; Barraclough *et al.*, 1983; Behaeghe, 1983; Ryden *et al.*, 1984; Jarvis and Cuttle, 1987; Simon *et al.*, 1989; Macduff *et al.*, 1990; Jarvis and Barraclough, 1991; Benke *et al.*, 1992; Garrett *et al.*, 1992; Watson *et al.*, 1992; Scholefield *et al.*, 1993; Decau and Le Corre, 1994; Decau and Salette, 1994; Vertès *et al.*, 1994; Farrugia *et al.*, 1997; Brown *et al.*, 2000). In general, nitrate-leaching losses from grassland increase with increasing N fertilization, in particular under grazing. In some cases, the losses under grazing are up to five times higher than under cutting. Hack-Ten Broeke (2000) assumed that under Dutch conditions the groundwater nitrate concentration will exceed the EC Nitrates Directive limit of 50 mg l^{-1} when nitrate-N leaching exceeds 34 kg ha^{-1} yr^{-1}. Figure 1 indicates that, with this assumption, excessive nitrate leaching may be expected when more than approximately 150 kg of

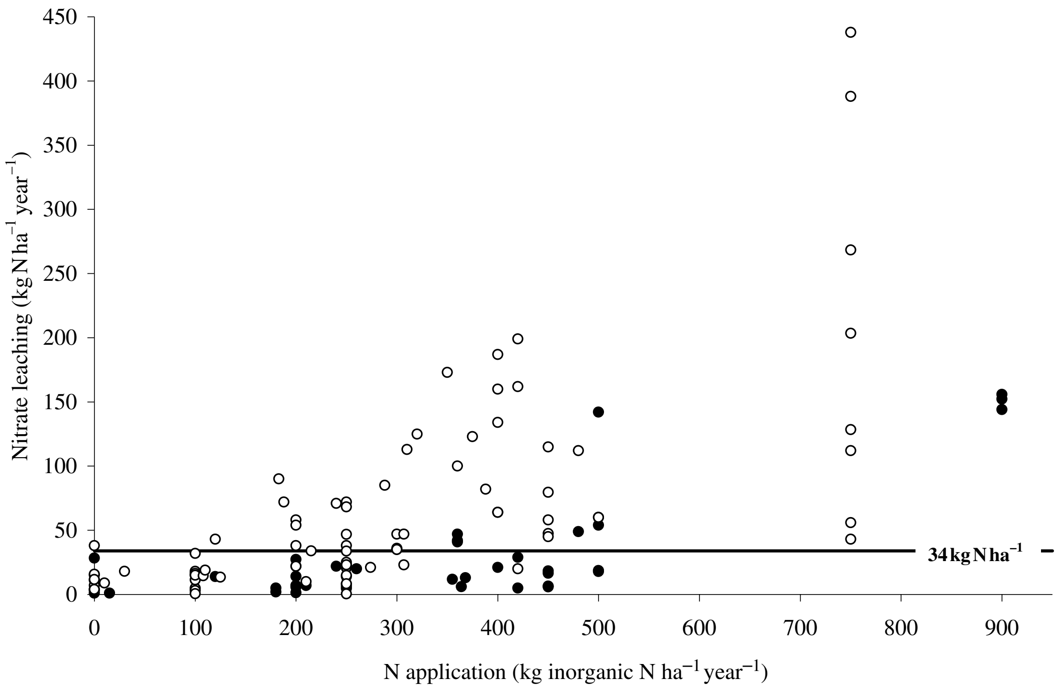

Figure 1 The amount of nitrogen leached from cut (◇) or grazed (◆) grasslands (based on nineteen literature references).

N ha^{-1} yr^{-1} is applied under grazing and when more than approximately 450 kg of N ha^{-1} yr^{-1} is applied under cutting. Willems *et al.* (2000), using results of Van der Meer and Meeuwissen (1989), drew a comparable conclusion. According to Deenen (1994), the optimal N application rate should be based on the amount of residual inorganic N at the end of the growing season rather than on an economic cost benefit analysis.

In Flanders, intensively managed grasslands comprise approximately 270 000 ha, an area corresponding to 0·41 of the total agricultural surface (Anonymous, 2001). In view of the current concern for N losses to ground- and surface-water, the Flemish Government has imposed legislation restricting the use of N fertilizer on arable land as well as on grassland (the 'Manure Action Plan'; Vlaamse Regering, 2000). Moreover, a limit on residual 'post-harvest' soil nitrate-N was established: in the period from 1 October to 15 November, no more than 90 kg of nitrate-N ha^{-1} should be present in the soil profile of 0–90 cm. Amounts of residual nitrate exceeding this limit might result in percolation of water with a nitrate concentration higher than 50 mg l^{-1} (De Clerq *et al.*, 2001). For sandy loam soils, a threshold of 70 kg of residual soil nitrate-N ha^{-1} would actually comply with the European Nitrates Directive for ground- and surface-water (Van Orshoven *et al.*, 2002).

The aim of the experiments described here was to determine and compare the economically optimal N fertilization rate (the N rate up to which extra yield pays for extra N input) and the N fertilization rate not resulting in excessive residual soil nitrate-N, on cut as well as on grazed grasslands. The research was conducted on a Flemish sandy loam soil, from 1995 to 2000.

Materials and methods

Cutting experiment

In 1995, an experiment was conducted on existing grassland (about 30 years old and never reseeded) on a sandy loam soil of the experimental farm of Ghent University at Melle, Belgium (50°59′N, 03°49′E, 11 m above sea level). The clay (<2 μm), silt (2–50 μm) and sand (>50 μm) contents of the top 27 cm of soil were 123, 566 and 311 g kg^{-1} respectively. At the start of the experiment (March 1995), the measurement of importance of plant species (determined according to the ranking method of De Vries, 1948) in the sward were 36% perennial ryegrass (*Lolium perenne* L.), 43% rough meadowgrass (*Poa trivialis* L.), 10% bent grasses (*Agrostis* spp.) and 8% white clover (*Trifolium repens* L.).

In a four-replicate block design, four levels of inorganic fertilizer were applied: 0, 100, 200 and 400 kg N ha^{-1} yr^{-1} (indicated as 0 N, 100 N, 200 N and 400 N, Table 1). For the 100 N and 200 N treatments, the N application was split into equal rates of 50 kg N ha^{-1}; for the 400 N treatment, the N application was split into rates decreasing progressively through the growing season (Table 1). The first N application was always applied in March; the subsequent N applications were applied immediately after successive cuts. Phosphorus (P) was applied following local advice for soils with a good P status. Potassium (K) was applied at a rate of 0·83 kg K kg^{-1} N applied. This is in accordance with the general guideline for cut swards: 0·75–1 kg K kg^{-1} N applied (Brown *et al.*, 1969; Brockman, 1971; Robson *et al.*, 1989). On the 0 N plots, the K rate was rather high (166 kg ha^{-1} yr^{-1}) to allow white clover to develop successfully. The plots were cut on a production-based schedule, aiming at yields of 3000–4000 kg dry matter (DM) ha^{-1} cut^{-1}. The grass was mowed with an engine-driven cutter bar mower; the cutting height was approximately 5 cm. Each individual experimental plot measured 58 m^2; the experimental area was 25·8 m^2. Nitrogen concentration (Kjeldahl-method), organic matter digestibility (OMD, Near Infrared Reflectance Spectroscopy) and crude ash concentration of the herbage of each cut were determined. The analyses were carried out in duplicate on herbage samples bulked per cut and per treatment.

The energy value of the herbage was determined following the method of the Centraal Veevoeder Bureau (C.V.B., 1992). According to this Dutch system, the energy value of forages is expressed as net energy for lactation (NEL, kJ kg^{-1} DM) and calculated as follows:

$$\mathrm{NEL} = 0{\cdot}6[1 + 0{\cdot}004(q - 57)]0{\cdot}9752\,\mathrm{ME},$$

where

$$\mathrm{ME} = \begin{cases} 14{\cdot}2\ \mathrm{DOM} + 5{\cdot}9\ \mathrm{DCP} & \text{if DOM/DCP} < 7 \\ 15{\cdot}5\ \mathrm{DOM} & \text{if DOM/DCP} > 7, \end{cases}$$

and q = 100 × ME/GE.

DOM = OMD(1000–ash)/100 and DOM = digestible organic matter (g kg^{-1} DM), OMD (organic matter digestibility, %), ash (g kg^{-1} DM) and DCP = 0·959 CP + 0·04 ash–40. DCP = digestible crude protein (g kg^{-1} DM) and CP = N-content × 6·25. ME = metab-metabolizable energy (kJ kg^{-1} DM) and GE = gross energy (kJ kg^{-1} DM). GE = 18000 kJ kg^{-1} DM (Andrieu *et al.*, 1988; Flachowsky, 1993).

Multiplying the DM yield of each cut by the corresponding energy value and adding up for all the cuts resulted in the annual energy yields for each of the fertilization treatments.

To express and evaluate the efficiency of applied fertilizer N, the apparent N effect (Deenen, 1994) or herbage yield response to applied fertilizer N was calculated as:

$$\text{Yield response } (X_1 \rightarrow X_2) = \frac{\text{Yield } (X_2) - \text{Yield } (X_1)}{X_2 - X_1}$$
$$(\text{kg DM kg}^{-1}\text{ N or GJ NEL kg}^{-1}\text{ N}),$$

X1, X2 = inorganic fertilizer rate (kg N ha^{-1} yr^{-1}).

At the end of the growing seasons (12 November 1996, 12 November 1997, 26 October 1998 and 8 November 1999), the amount of residual soil nitrate-N was measured. On each individual plot, four random areas were sampled using gauge augers. Three soil depths were sampled: A (0–30 cm), B (30–60 cm) and C (60–90 cm). For each treatment and each soil depth, the twelve soil cores (3 plots × 4 cores per plot) were bulked, two sub-samples of 30 g were extracted with a 1% $KAl(SO4)_2$-solution and the nitrate concentration was measured in duplicate with a nitrate-specific electrode (Cottenie and Velghe, 1973; Hofman, 1983).

On 31 March 1998 and 18 September 2000, within each individual plot in forty quadrats of 10 cm × 10 cm, white clover presence was determined (Kent and Coker, 1992). Measurement of frequency is a good alternative for density measurements when clonal species (e.g. white clover) are present (Whalley and Hardy, 2000). On 27 March 1998, a botanical analysis according to the method of De Vries (1933, 1948) was also carried out. This method is a dry-weight ranking method, which is the simplest procedure for estimating

Table 1 Amounts of nitrogen (N), phosphorus (P) and potassium (K) fertilizer (kg ha^{-1}) applied to the experimental treatments in the cutting and grazing experiments.

Treatment	N (split applications)	P	K (split applications)
Cutting experiment			
0 N	0	35	166 (83-83)
100 N	100 (50-50)	35	83 (42-42)
200 N	200 (50-50-50-50)	35	166 (83-83)
400 N	400 (100-90-80-70-60)	35	332 (116-108-108)
Grazing experiment			
0 N	0	26	42 (25-17)
200 N	200 (50-50-50-50)	26	42 (25-17)
400 N	400 (80-80-80-80-80)	26	42 (25-17)

N, calcium ammonium nitrate (27%); P, triple superphosphate (43%); K, muriate of potash (40%).

the proportion by dry weight of the different species in grassland (Whalley and Hardy, 2000). On each plot, forty samples (forty cores corresponding with an area of 28·3 cm^2 each) were analysed after ten growing days in a greenhouse.

Grazing experiment

A grazing experiment was conducted in the spring of 1996 at the same site. Three N fertilizer treatments were carried out in a 3 × 3 Latin square: 0, 200 or 400 kg inorganic N ha^{-1} yr^{-1} (Table 1). Phosphorus was applied at 26 kg ha^{-1}, following local advice for soils with a good P status. As grazing heifers return a large amount of nutrients in faeces and in urine, the net K uptake is very low. According to Williams (1980) and Van de Ven (1990), 15–42 kg K ha^{-1} yr^{-1} should be adequate to meet the needs of a grazed sward. In this experiment, K was applied at 42 kg ha^{-1}.

Heifers (average age and live weight at the start of the growing season: 14 months and 354 kg respectively) rotationally grazed the nine paddocks, each measuring 975 m^2. The heifers were moved to the next plot when the herbage was grazed down to a height of approximately 7 cm. Buffer strips with a total area of 3000 m^2 were available for grazing during periods of shortage on the experimental plots. The grazing seasons of 1996, 1997, 1998 and 1999 started on 29, 18, 21 and 28 April, respectively, and lasted 178, 161, 178 and 176 d respectively.

Plot-to-plot nutrient carry-over by the excreta of the heifers would have occurred. Nevertheless, nutrient translocations by animals moving to a next paddock was always compensated by nutrient input by the animals entering again from another paddock during the next grazing round. As the plot grazing sequence was altered for each grazing round, these compensations were randomized in the long term.

Total grass yields were calculated by measuring heifer performance during grazing (Woolfolk, 1962; Lantinga *et al.*, 1987; Coates and Penning, 2000). According to Bransby and Maclaurin (2000), total heifer production ha^{-1} can be calculated as PH × SR × T, where PH is the daily production per heifer (kg), SR is the stocking rate (heifers ha^{-1}) and *T* is the grazing time in days.

SR and *T* were derived from recording the number of heifers (five to eight, depending on the availability of grass during the grazing season) and the duration of the subsequent grazing periods on each of the individual experimental plots. To determine PH, the live weight-based daily energy demands of growing and grazing heifers currently used in the Netherlands (I.K.C., 1993) were applied. These demands are expressed as Dutch Feed Units [VEM = 'Voedereenheid Melk (Dutch Feed Unit milk)] (Table 2). The VEM values were transformed into GJ ha^{-1}, assuming that 1 VEM corresponds to 6·9 kJ NEL (Van Es, 1978; Deenen and Lantinga, 1993). At the start of the grazing season, the heifers were weighed after an adaptation period of about 8 d of grazing on the buffer plots. During the grazing season, the animals were weighed at intervals of 1 month and finally when they returned to the cowshed in October.

There is a possible inherent lack of precision in the estimation of absolute grassland productivity as it was based on theoretical energy demands and not on direct measurements. Nevertheless, the method used has proved to be useful for obtaining relative measures of herbage intake in pastures (Baker, 1982; Deenen and Lantinga, 1993) and this was the major objective of this research, i.e. comparing productivity of swards at different N application rates. In addition, other methods show drawbacks, e.g. measuring grazed grassland yields by herbage accumulation under exclosure cages tends to overestimate herbage intake (Deenen and Lantinga, 1993).

Moreover, the method used incorporates grazing time as a response variable as grazing was ended on different treatments or plots at different times, based on an objective criterion – canopy height. According to Bransby and Maclaurin (2000), this time factor is often completely overlooked in experiments measuring animal production.

The N yield in liveweight gain was calculated for each fertilizer treatment by multiplying observed liveweight gains by an average N concentration of 25 g kg^{-1} (Carlier *et al.*, 1992; Anonymous, 2000a).

In the same way as in the cutting experiment, at the end of the growing season soil samples were taken to determine the amount of residual nitrate-N. However, on these larger and grazed plots (on which a larger variability was expected), the number of cores was increased to ten in each plot and a bulked sample of each individual plot was analysed in duplicate. The methods of analysis were the same as in the cutting experiment.

On 27 March 1998 in forty quadrats of 10 cm × 10 cm in each plot, the presence of white clover was determined (as in the cutting experiment). On the same date, a botanical analysis, according to the

Table 2 Net energy (NE) demand (MJ NEL day^{-1}) of growing dairy heifers as a function of their live weight (kg).

Live weight	**175**	**225**	**265**	**305**	**350**	**385**	**425**	**460**	**500**
NE demand	29·0	35·2	35·9	39·7	44·2	46·2	50·0	54·9	61·4

method of De Vries (1933, 1948), was also carried out. On each plot, forty core samples each of 28·3 cm^2 were analysed.

On-site weather data for the growing seasons are shown in Figures 2 and 3.

Statistical analyses

Analyses of variance were performed using the STATITCF software package of INRA (Institut National de la Recherche Agronomique, France). Homogenous groups were determined using the test of Newman-Keuls.

Results and discussion

Cutting experiment

Botanical composition

Significant botanical shifts occurred in the grassland (Table 3). The presence of white clover increased strongly in the 0 N and the 100 N swards and its frequency and importance percentage were significantly higher ($P < 0{\cdot}001$) than in the 200 N and the 400 N plots. The white clover content increased at the expense of *L. perenne*: compared with an initial value of 36%, the percentage of perennial ryegrass on the 0 N and 100 N plots decreased to 15% and 19% respectively. On the 200 N and 400 N plots, the presence of *L. perenne* increased to 39% and 49%, respectively, when measured in March 1998.

Dry-matter yield

The DM yields from 1995 to 2000 are summarized in Figure 4. When compared with references in the literature (Hopkins, 2000), the yields of the 400 N treatment (on average 16·6 Mg DM ha^{-1} yr^{-1}) illustrate a very high production on the site. On the 100 N and 200 N plots high average yields were obtained – 13·8 and 14·7 Mg DM ha^{-1} yr^{-1} respectively. The DM yields reflected the growing conditions and management in an experiment which are better, on average, than on a farm. Moreover, under practical conditions, harvesting, conservation and feeding losses occur, resulting in lower net yields. These losses will not be considered in the discussion on optimal rate of N as they only change the height of the response curves, not the slopes.

The variability of DM yield and N response among years was quite high (Hopkins, 2000). Elgersma *et al.* (1998) found high yield variability owing to the white clover content changing between years.

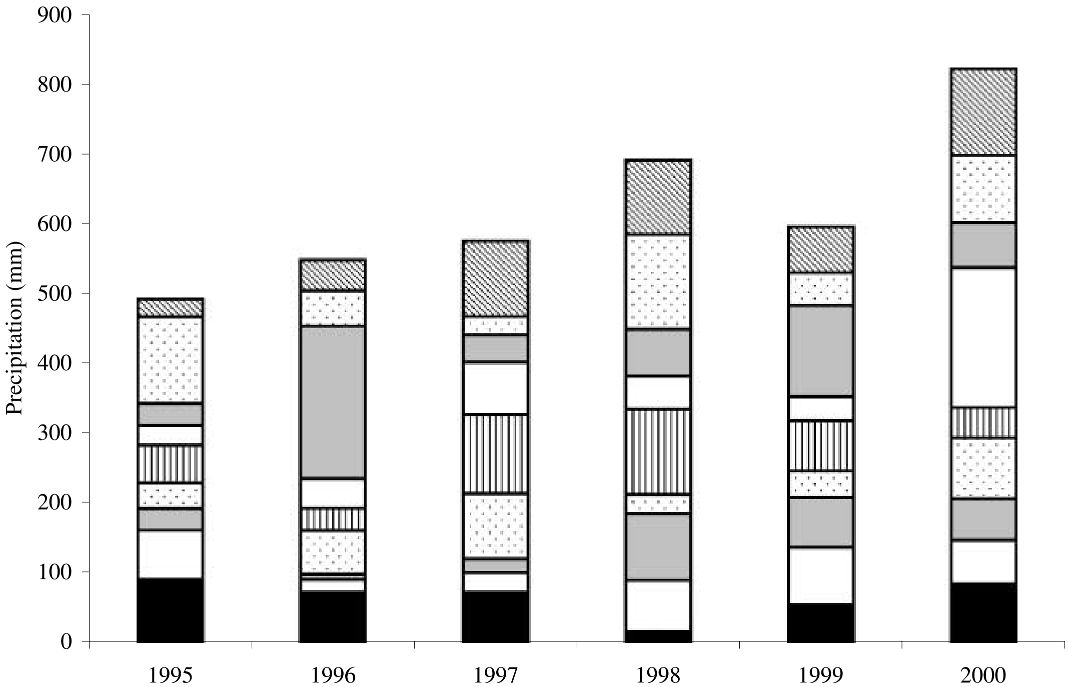

Figure 2 Precipitation during the growing season at Melle, 1995–2000: (▨ October; ▨ September; ■ August; □ July; ▥ June; ▨ May; ■ April; □ March; ■ February).

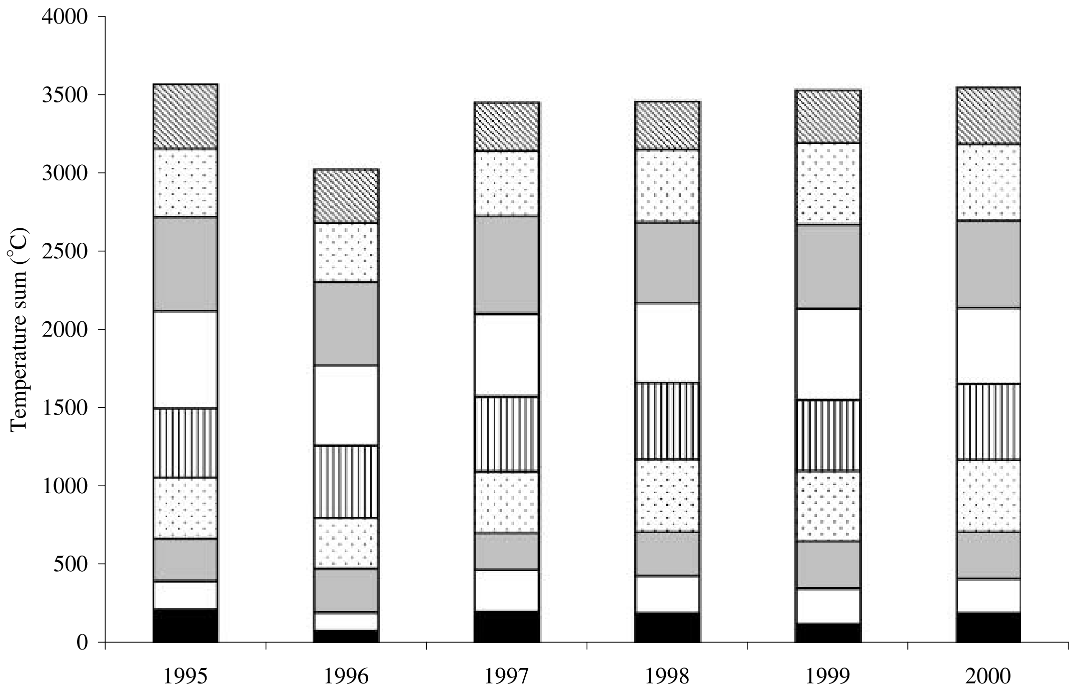

Figure 3 Temperature sum (addition of the positive average daily temperatures) during the growing season at Melle, 1995–2000: (from top to bottom of each histogram: ▧ October; ▨ September; ■ August; □ July; ▥ June; ▨ May; ■ April; □ March; ■ February).

Table 3 Importance percentage of plant species and frequency of *Trifolium repens* in the swards to which N fertilizer treatments were applied in the cutting experiment.

	N rate (kg ha^{-1} yr^{-1})				
Species	**0**	**100**	**200**	**400**	**Significance of N rate**
Importance percentage on 15 March 1995					
Lolium perenne L.		35·9			
Poa trivialis L.		43·4			
Agrostis spp.		9·6			
Trifolium repens L.		7·6			
Importance percentage on 31 March 1998					
Lolium perenne L.	15·0[c]	18·5[c]	39·4[b]	49·1[a]	***
Poa trivialis L.	37·8[a]	36·9[a]	41·3[a]	36·7[a]	NS
Agrostis spp.	7·1[a]	6·6[a]	6·4[a]	8·7[a]	NS
Trifolium repens L.	32·9[a]	28·4[a]	9·2[b]	2·6[b]	***
Frequency (%) of *Trifolium repens* L.					
31 March 1998	97·0[a]	86·0[a]	50·0[b]	12·0[c]	***
18 September 2000	93·8[a]	90·6[a]	62·5[b]	13·8[c]	***

Within one row, values with different letters are significantly different at $P < 0{\cdot}05$ (Newman-Keuls test).
***$P < 0{\cdot}001$; NS, non-significant.

Relative to the 6-year mean of DM yield at 400 N, the DM yield was 0·88, 0·83 and 0·69 of the 200 N, 100 N and 0 N treatments respectively. As a result of the increasing amount of white clover in the 0 N sward, a remarkably high yield was obtained on these plots from 1997 onwards. Another factor allowing relatively high yields under zero or low N-fertilization was the yield-based cutting regime. Compared with a much easier to perform time-based regime, the cutting system used allowed longer growing periods and hence higher yields on the less fertilized plots (Holliday and Wilman, 1965). According to Wilman and Asiegbu (1982) and

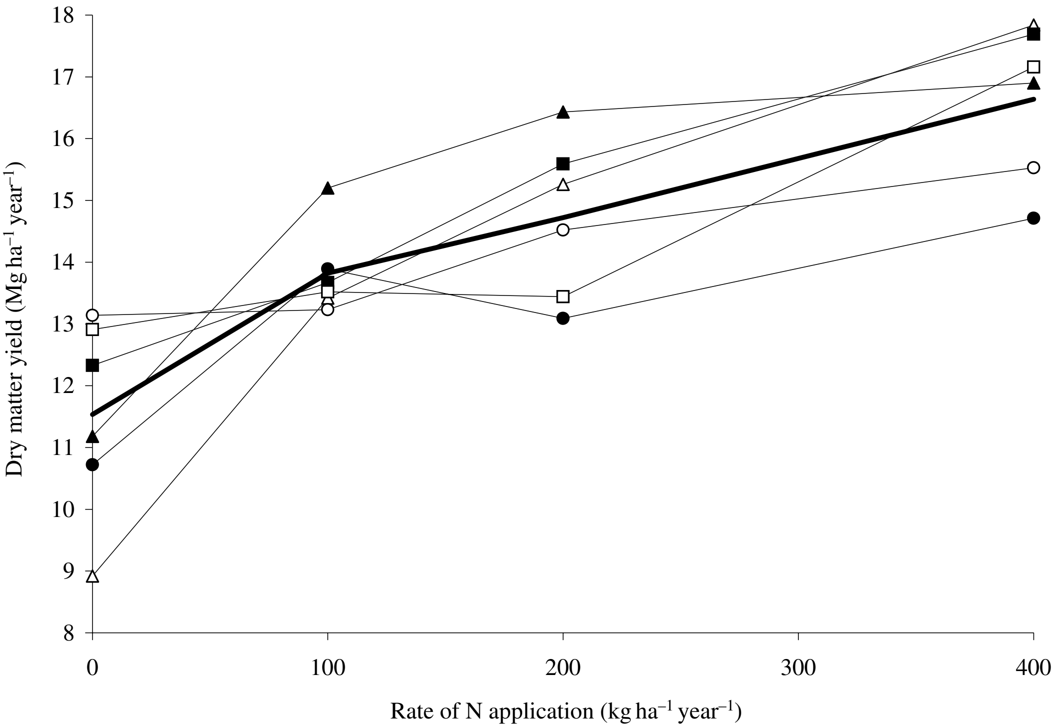

Figure 4 Dry-matter yields in the cutting experiment in 1995 (▲), 1996 (△), 1997 (■), 1998 (□), 1999 (●) and 2000 (○) (bold line is mean).

Lehmann *et al.* (2001), in mixed swards with a low N application rate, white clover performs better if rather long intervals between harvests are allowed. Holliday and Wilman (1965), Reid (1970), Boxem (1973), Van Steenbergen (1977), Sibma and Alberda (1980) and Wieringa *et al.* (1980) emphasized the importance of the cutting regime adopted in studying the yield response of grass/white clover swards to N applications. A yield-based cutting schedule combined with good establishment and growing opportunities for white clover is a prerequisite to an agronomically significant and a practically oriented image of the yield response of grasslands to applied N.

Linehan and Lowe (1960) illustrated the differences in herbage yield as well as the yield response to N between first and subsequent seasons of newly established grasslands, owing to changes in the botanical composition (particularly changes in white clover content). In agreement with the findings of Jackson and Williams (1979) and Cowling (1961), the yield response to applied N was larger during the initial seasons of the experiment, when white clover was not yet fully established. Starting from 1997 (when white clover was well established), an increase in N fertilization level from 0 to 100 kg N ha^{-1} yr^{-1} resulted in an average yearly yield response of 1·30 Mg DM ha^{-1} or 13 kg DM kg^{-1} applied N. This response to applied N is lower than in ryegrass-dominated swards (Hopkins *et al.*, 1995; Frame *et al.*, 1998; Hopkins, 2000) but corresponds quite well with the average yield response of grass-clover swards of 10–12 kg DM kg^{-1} N suggested by Whitehead (1995) and the values of 11 kg DM kg^{-1} N by Davies and Williams (1958), 14 kg DM kg^{-1} N by Orr and Laidlaw (1978), 16 kg DM kg^{-1} N by Laidlaw (1980) and 7·4–11·6 kg DM kg^{-1} N by Shils (1997). An increase in the rate of N application from 100 to 200 kg ha^{-1} yr^{-1} increased the average DM yield by 0·58 Mg ha^{-1} yr^{-1}. This represents a response of only 5·8 kg DM kg^{-1} N. Elgersma *et al.* (2000) and Schils (2002) also compared different N treatments on a newly established grass/white clover sward. Compared with the 0 N treatment, application of 180 or 190 kg N ha^{-1} yr^{-1} did not increase total DM yield: an increased grass DM yield was offset by a decreased white clover yield. The increase from 200 to 400 kg N ha^{-1} yr^{-1} in N fertilizer applied increased the yield by 2·11 Mg DM ha^{-1} yr^{-1}, corresponding to a response of 10·6 kg DM kg^{-1} N.

When optimizing N fertilization from an economic point of view, it is important to know the N rate limit above which the resulting yield increase does not pay for the extra N input (Lantinga *et al.*, 1987). According

Table 4 Net energy yields (GJ NEL ha^{-1} yr^{-1}) of herbage in the cutting experiment.

Year	N rate (kg ha^{-1} yr^{-1}) 0	100	200	400	Significance of N rate
1995	55·8^{c}	84·6^{b}	89·4^{b}	95·7^{a}	***
1996	48·9^{d}	80·0^{c}	94·9^{b}	108·2^{a}	***
1997	73·7^{c}	79·8^{c}	91·2^{b}	105·8^{a}	***
1998	76·6^{b}	80·3^{b}	80·4^{b}	103·0^{a}	***
1999	58·6^{c}	70·1^{b}	68·4^{b}	77·7^{a}	**
2000	68·3^{c}	71·4^{c}	77·8^{b}	84·7^{a}	***
Total 1995–2000	382·1^{c}	466·3^{b}	502·1^{b}	575·1^{a}	***
Average 1995–2000	63·7^{c}	77·7^{b}	83·7^{b}	95·9^{a}	***
Relative to 400 N	0·664	0·811	0·873	1·00	
Total 1997–2000	277·1^{c}	301·3^{bc}	317·8^{b}	370·9^{a}	***
Average 1997–2000	69·3	75·3	79·5	92·7	***
Relative to 400 N	0·747	0·812	0·857	1·00	

Within one row, values with different letters are significantly different at $\alpha = 0{\cdot}05$ (Newman–Keuls test).
**, $P < 0{\cdot}01$; ***, $P < 0{\cdot}001$.

to Neeteson and Wadman (1987), the N level at which the herbage response falls to the cost value ratio (cvr) is the economic optimum. When maize silage was considered as a potential forage to purchase in replacement of grass silage, and with local Flemish prices (Anonymous, 2000b), the resulting critical cvr was:

$$\text{cvr} = \frac{\text{Cost of 1 kg of mineral fertilizer N (application included)}}{\text{Purchase price of 1 kg of silage maize DM}} = \frac{€0.625}{€0.062} = 10€.$$

This value of 10 also corresponds to the critical response limit applied by Morrison *et al.* (1980). With this critical value, the increase of N application from 0 to 100 kg ha^{-1} yr^{-1} was economically justified during the growing seasons of 1997, 1998, 1999 and 2000. A further increase to 200 kg N ha^{-1} yr^{-1} was not an economic option. Increasing the N application from 0 to 400 kg N ha^{-1} yr^{-1} was economically justified as the response of 10 kg DM kg^{-1} N was met again. Possibly even more N could have resulted in a still higher response, as the grass yield under mowing management in Western Europe can continue to respond significantly up to 400–700 kg N ha^{-1} yr^{-1}, depending on soil type and growing conditions ('t Mannetje and Jarvis, 1990). Behaeghe and Carlier (1973) found that even up to 600 kg N ha^{-1} yr^{-1} the yield response did not drop below 10 kg DM kg^{-1} N on the Melle experimental site. Morrison *et al.* (1980), using a marginal profitability of 10 kg DM kg^{-1} N, found average optimum N rates between 388 and 530 kg ha^{-1} yr^{-1} in mowed perennial ryegrass plots. Assuming a marginal profitability of 7·5 kg DM kg^{-1} N, Prins (1983) found an average optimum N rate of 420 kg ha^{-1} yr^{-1} (range of 360–520 kg ha^{-1} yr^{-1}) on Dutch sand and clay soils. Deenen (1994) found an average optimum N rate of 430 kg ha^{-1} yr^{-1} on sandy soils.

Herbage net energy yield

Table 4 summarizes the net energy yields (NEL) in the cutting experiment. The average yield of 95·9 GJ NEL ha^{-1} for the 400 N treatment is high, but corresponds well with the findings of Deenen and Lantinga (1993) and Lantinga and Groot (1996). Relative to the 6-year NEL yield of the 400 N treatment, the 200 N, 100 N and 0 N yields were 0·87, 0·81 and 0·66 respectively. These relative values correspond well to those found when comparing DM yields, indicating that the average feed energy contents of the herbage on the four N treatments were comparable. On average, the 100 N plots outyielded the 0 N plots by 14·0 GJ NEL ha^{-1} yr^{-1}. Increasing N fertilization from 100 to 200 kg ha^{-1} yr^{-1} resulted in a smaller yield increase of 6·0 GJ NEL ha^{-1} yr^{-1}. Over the 6-year period of the experiment, the yields of the 100 N and 200 N treatments were not significantly different. A further increase in the N level from 200 to 400 kg ha^{-1} yr^{-1} again resulted in a significant increase in feed energy yield of 12·2 GJ NEL ha^{-1} yr^{-1}. Considering the period with full white clover development (from 1997 onwards), the average yield responses to applied N for the N levels of 0–100, 100–200 and 200–400 kg ha^{-1} yr^{-1} were 60·5, 41·3 and 66·4 MJ NEL kg^{-1} N respectively.

Following Neeteson and Wadman (1987) again, the critical yield response was determined as the ratio of the local cost of 1 kg N in mineral fertilizer (€0·625) to the purchase price of 1 MJ NEL in silage maize (€0·011).

This resulted in a critical yield response value of 57 MJ NEL kg^{-1} N applied. At this critical cvr, increasing the N-fertilization rate from 0 to 100 kg ha^{-1} yr^{-1} was an economically sensible decision. As a further increase to 200 kg N ha^{-1} yr^{-1} was reflected in a yield response of only 41·3 MJ NEL kg^{-1} N applied, increasing N fertilization from 100 to 200 kg ha^{-1} yr^{-1} was not economic. However, increasing from 100 to 400 kg N ha^{-1} yr^{-1} resulted in an increase of 58 MJ NEL kg^{-1} N (a response just reaching the critical cvr) and hence was economically justified.

These findings reflect the importance of white clover presence in the sward for judging optimal N fertilizer use. Applying 100 kg N ha^{-1} yr^{-1} (in two spring dressings of 50 kg N ha^{-1}) resulted in a significant and economically justified increase in DM as well as in NEL yield compared with the 0 N plots. Morrison *et al.* (1983) highlighted the potential of moderate N rates to overcome seasonal deficiencies in production of grass/white clover swards but an increased herbage production must always be weighed against the depressive effects on white clover performance when increased N fertilizer use is considered (Frame and Boyd, 1986, 1987; Frame and Newbould, 1986). Compared with the 0 N plots, the white clover content of the 100 N sward was somewhat depressed, although not significantly (Table 3). Compared with the 100 N plots, the addition of N fertilizer to the 200 N plots clearly reduced the white clover content, but the resulting extra grass growth compensated for the yield loss through the disappearance of white clover and the net yield result of the extra 100 kg N ha^{-1} was not significant. This illustrates that when white clover is given high priority, N fertilization should only be used strategically during spring and at low levels (Laidlaw, 1980, 1984; Frame and Boyd, 1987; Baars, 2001; Schils, 2002). On the 400 N plots, white clover nearly disappeared and the high NEL yield was the result of rapid grass growth at high N availability from mineral fertilizer.

These results suggest a two-track N fertilization management: either low N use (no more than 100 kg N ha^{-1} yr^{-1}) to take maximum advantage of white clover; or use fertilizer N intensively, knowing that a fertilizer level of 400 kg N ha^{-1} yr^{-1} (or even more) is economically justified. A similar two-track decision schedule was also indicated by Schils (2002). Reid (1983) concluded that the N rates required for an annual yield of 12 Mg DM ha^{-1} were 340 kg ha^{-1} in a pure perennial ryegrass sward and 140 kg ha^{-1} on a perennial ryegrass/white clover sward. The statement of Armitage and Templeman (1964) that the use of fertilizer N should be preferred to a reliance on white clover to obtain the highest DM yields is also in line with the results.

Nitrogen yields

Table 5 describes the N yields of the cut grassland. The N yield of the 400 N treatment (on average 429 kg ha^{-1} yr^{-1}) was always significantly higher than the N yields on the other treatments. Compared with 100 N treatment, the 200 N treatment had a significantly higher N yield in 1995 and 1996. However, from 1997 onwards, the N yields of the 0 N, 100 N and 200 N treatments did not differ significantly except that the N yield of the 0 N treatment was significantly lower in 2000. In 1995 and 1996, when

Table 5 Nitrogen yields (kg ha^{-1} yr^{-1}) at a range of N fertilizer rates in the cutting experiment.

Year	N rate (kg ha^{-1} yr^{-1}) 0	100	200	400	Significance of N rate
1995	154^{d}	290^{c}	323^{b}	456^{a}	***
1996	150^{d}	266^{c}	299^{b}	509^{a}	***
1997	302^{b}	291^{b}	276^{b}	416^{a}	***
1998	281^{b}	274^{b}	294^{b}	441^{a}	***
1999	237^{b}	261^{b}	243^{b}	292^{a}	**
2000	287^{c}	350^{b}	365^{b}	461^{a}	***
Total 1995–2000	1411^{c}	1732^{b}	1799^{b}	2576^{a}	***
Average 1995–2000	235^{c}	289^{b}	300^{b}	429^{a}	***
Relative to 400 N	0·548	0·672	0·698	1·00	
Total 1997–2000	1107^{b}	1176^{b}	1178^{b}	1610^{a}	***
Average 1997–2000	277^{b}	294^{b}	295^{b}	403^{a}	***
Relative to 400 N	68·7	73·0	73·2	100	

Within one row, values with different letters are significantly different at $P < 0.05$ (Newman–Keuls test).
**, $P < 0.01$; ***, $P < 0.001$.

white clover was not yet established, the N yields on the 0 N plots were low. From 1997 onwards and owing to the rising white clover content, these N yields increased and were higher than those from *L. perenne*-dominated swards without N fertilization (Hopkins *et al.*, 1995). Compared with the DM yields, the relative N yields show a greater difference between the 400 N and the other treatments. This indicates a higher N concentration of the herbage harvested at the highest N rate. Figure 5 confirms this. The herbage on the 400 N treatment contained about 26 g N kg^{-1} DM for cuts between 3 and 5 Mg DM ha^{-1}. In the same yield range, an average N concentration of 20 g kg^{-1} DM was observed for the 0 N, 100 N and 200 N treatments. In 1995 and 1996 there were low N concentrations on the 0 N treatment (14–17 g N kg^{-1} DM) but with increasing white clover development these contents rose to averages of 20 (cut at 4 Mg DM ha^{-1}) to 29 (cut at 2 Mg DM ha^{-1}) g N kg^{-1} DM.

Residual soil nitrate-N

The amounts of residual soil nitrate-N (N_{res}) are presented in Figure 6. The relatively low amounts of N_{res} for cut grassland correspond well with other studies. Alberda (1971) concluded that high amounts of N fertilizer could be applied to cut grassland without risk of excessive nitrate leaching. From the results of this study (and accepting the 90 kg ha^{-1} threshold on residual N), it is concluded that, at least up to an application of 400 kg N ha^{-1} yr^{-1}, no excessive leaching should occur. This is in agreement with Prins (1983) who concluded that up to the economically optimal N rate, the risks of N-leaching from cut swards are minimal. Even if we assume an arbitrary threshold value of only 70 kg residual nitrate-N ha^{-1}, fertilizing at the economically optimal N rate would cause no excessive amounts of residual soil nitrate.

Grazing experiment

Botanical changes

Although no statistically significant differences were observed, the frequency of white clover at the start of the 1998 grazing season was higher on the 0 N treatment than on the 200 N and 400 N treatments (Table 6). However, white clover contents did not increase to the same extent as in the cutting experiment, except at 400 N. The lower presence of white clover on grazed grassland is consistent with the findings of Brockman and Wolton (1963) and was probably due to the recirculation of N through the heifers. The decrease of *L. perenne* in the 0 N plots was not just due to an increase in the content of white

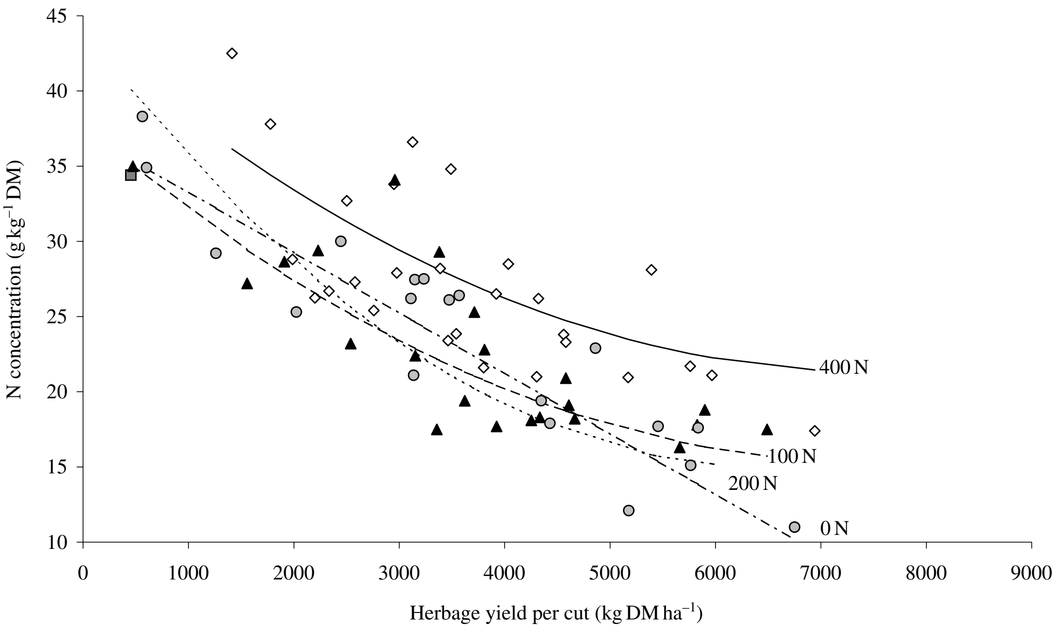

Figure 5 N concentration of the harvested herbage for each cut of the four N treatments (◇, 400 N; ■, 200 N; ▲, 100 N and ●, 0 N).

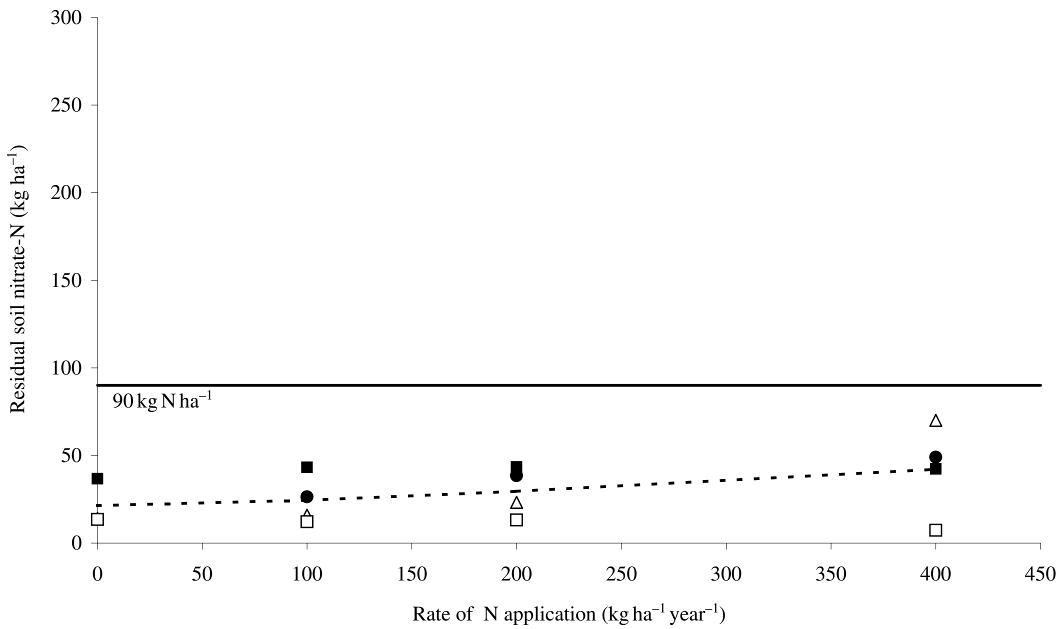

Figure 6 Residual soil nitrate-N (kg ha^{-1}; 0–90 cm) in the cut swards after the growing seasons of 1996 (△), 1997 (■), 1998 (□) and 1999 (●). (Mean value is given by the dashed line).

Table 6 Importance percentage of plant species and frequency of *Trifolium repens* L. in the swards receiving the N fertilizer application rates in the grazing experiment.

Species	N rate (kg ha^{-1} yr^{-1}) 0	200	400	Significance of N rate
Importance percentage on 15 March 1995				
Lolium perenne L.		35·9		
Poa trivialis L.		43·4		
Agrostis spp.		9·6		
Trifolium repens L.		7·6		
Importance percentage on 27 March 1998				
Lolium perenne L.	26·0[b]	47·3[a]	49·5[a]	*
Poa trivialis L.	33·1	32·2	29·8	NS
Agrostis spp.	22·3	6·8	8·4	NS
Trifolium repens L.	14·4	11·4	8·5	NS
Frequency (%) of *Trifolium repens* L.				
27 March 1998	59·3	36·0	30·0	NS

Within one year, values with different letters are significantly different at $P < 0·05$ (Newman–Keuls test).
*, $P < 0·05$; NS, non-significant.

clover but also due to an expansion in the content of *Agrostis* species. In March 1998, the presence of *L. perenne* in the 200 N and 400 N plots (47% and 50% respectively) had increased compared with the initial year of 1995 (36%) (Table 6).

Herbage net energy yield

The NEL yields of the 0 N, 200 N and 400 N treatments are summarized in Table 7. The average yields of 71–74 GJ NEL ha^{-1} yr^{-1} on the 200 N and 400 N grazed swards correspond well with the values of Deenen and Lantinga (1993), Lantinga and Groot (1996), Berentsen *et al.* (2000) and Mayne *et al.* (2000). The 31-year (1969–99) average yield on adjacent grazed permanent grassland at the Melle experimental site was 75·1 GJ NEL ha^{-1} yr^{-1} (Nevens and Reheul, 2003). There was a high variability in the NEL yield of the grazed grassland. The highest yield was 84·4 GJ NEL ha^{-1} in 1997 and the lowest yield was 5·3 GJ NEL ha^{-1} in 1999. This high between-year yield variability on grazed grasslands, often larger than differences in the rate of N fertilizer application, is not new (Anonymous, 1999).

In three of four grazing seasons, the 200 N treatment resulted in a significantly higher NEL yield than the 0 N treatment but no significant yield difference between the 200 N and the 400 N paddocks was observed. Increasing the rate of N application from 0 to 200 kg ha^{-1} yr^{-1} on this grazed grassland was economically justified as the average yield response of 110 MJ NEL kg^{-1} N exceeded the critical cvr of 57 MJ NEL kg^{-1} N. A further increase in N fertilizer rate from 200 to 400 kg ha^{-1} yr^{-1} was not economically

Table 7 Net energy yields (GJ NEL ha^{-1} yr^{-1}) at a range of N fertilizer rates of herbage in the grazing experiment

Year	N rate (kg ha^{-1} yr^{-1}) 0	200	400	Significance of N rate
1996	45·4[b]	77·5[a]	84·1[a]	*
1997	53·2[b]	84·1[a]	84·4[a]	*
1998	59·6[a]	69·8[a]	68·4[a]	NS
1999	39·1[b]	53·5[a]	58·3[a]	*
Total 1996–99	197·2[b]	284·9[a]	295·1[a]	*
Average 1996–99	49·3[b]	71·2[a]	73·8[a]	*
Relative to 400 N	0·668	0·965	1·00	

Within one row, values with different letters are significantly different at $P < 0{\cdot}05$ (Newman–Keuls test).
*, $P < 0{\cdot}05$; NS, non-significant.

Table 8 N yields (kg ha^{-1} yr^{-1}) at a range of N fertilizer rates in the grazing experiment.

Year	N rate (kg ha^{-1} yr^{-1}) 0	200	400
1996	10·1	17·3	18·7
1997	21·1	33·3	33·4
1998	19·1	22·3	21·9
1999	18·5	26·8	27·7
Total 1996–99	68·8	99·7	101·7
Average 1996–99	17·2	24·9	25·4
Relative to 400 N	0·677	0·980	1·00

justified, as the yield response was only 13 MJ NEL kg^{-1} N. Jackson and Williams (1979) also found no significant response in grazed grassland yields when the N rate was increased from 200 to 400 kg ha^{-1} yr^{-1}. The yield response of grazed grassland in this higher N application range is well below the yield response of cut grassland (Deenen, 1994; Whitehead, 1995). The results reported here are in agreement with those of Deenen (1994) and Jackson and Williams (1979), who estimated that the optimum N application rate under grazing is some 200 kg ha^{-1} yr^{-1} less than under cutting. A study in Germany suggested that the economically optimum N rate for grassland grazed by heifers is no more than 100 kg ha^{-1} yr^{-1} (Anonymous, 1999).

Compared with the cut plots (1996–99), the grazed 0 N, 200 N and 400 N plots yielded 0·77, 0·85 and 0·75 of NEL respectively. Lantinga *et al.* (1987) obtained similar results with an approximately 0·20 lower yield under grazing (at N fertilizer rates of 214 and 427 kg ha^{-1} yr^{-1}). The lower yields under grazing result from the higher frequency of defoliation (Sibma and Alberda, 1980) and the adverse effects on the sward through treading, selective grazing and fouling of herbage by dung (Whitehead, 1995). These adverse effects exceeded the potential positive effect of nutrient return through excreta.

As mentioned previously, the yields observed in the cutting experiment are overestimated as field and conservation losses were not taken into account. On average, field and conservation losses are estimated at 0·15–0·20 of DM yield under an optimal conservation management (2 d of field drying prior to ensiling at a DM content of 350 g kg^{-1} (Nevens and Reheul, 1999). This brings the net yield under cutting close to the yield under grazing.

Nitrogen yield

The amounts of N deposited by the growing heifers at the end of the grazing seasons are presented in Table 8. There are discrepancies between observed N yield and net energy yield (Table 7) due to between-season differences in initial live weight of the heifers and their liveweight gain. N yields only comprise the observed liveweight gain while energy yields comprise both energy needed for liveweight gain and maintenance. Heavier and/or slower-growing animals use relatively more energy for maintenance than for growing; hence they yield less N per unit of net energy.

The observed N yields were very small. A maximum N yield of 33 kg ha^{-1} yr^{-1} (400 N treatment in 1997) and average values from 1996 to 1999 of 17, 25 and 25 kg ha^{-1} yr^{-1} on the 0 N, 200 N and 400 N treatments respectively. These N yields represent 0·06–0·08 of the yields from the cut plots. Weissbach and Ernst (1994) also reported comparable low N yields or translocations in grazing systems with heifers: 14–19 kg ha^{-1} yr^{-1} at N-application rates of 0 and 330 kg ha^{-1} yr^{-1} respectively. Van der Putten and Vellinga (1996) estimated maximum N translocations by growing cattle of 33 kg ha^{-1} yr^{-1} at N-application rates of 240, 360 and 480 kg ha^{-1} yr^{-1} respectively.

Residual soil nitrate-N

On the 0 N treatment, the amounts of residual soil nitrate-N were comparable with those found on the 0 N treatments under cutting and were always well below 90 kg ha^{-1} (Figure 7). On the 200 N grazed plots, the average of 77 kg residual nitrate-N ha^{-1} came close to the threshold value; in one of the four seasons (1997) the limit was actually exceeded (99 kg nitrate-N ha^{-1}). Applying 400 kg N ha^{-1} yr^{-1} on the grazed plots resulted in very high amounts of residual soil nitrate-N, as after each grazing season high amounts of residual soil nitrate-N were left in the soil profile with up to a maximum of 289 kg N ha^{-1} in 1996 (Figure 7). The large return of excreted N in local concentrations far beyond the demand of the herbage resulted in accumulation of nitrate-N, which is prone to leaching during winter (Ball and Keeney, 1981; Deenen, 1994). If an arbitrary threshold value of only 70 kg residual nitrate-N ha^{-1} is assumed, the ecologically optimum N fertilizer rate would be about 150 kg ha^{-1}. This optimum rate corresponds quite well with the results of the literature review (Figure 1).

Weissbach and Ernst (1994) compared grass/clover swards receiving 46 kg N ha^{-1} yr^{-1} with pure grass swards receiving 377 kg N ha^{-1} yr^{-1}. The amount of inorganic N in the upper 100 cm of soil in autumn was less than 100 kg ha^{-1} for the lower and 200–300 kg ha^{-1} for the higher rate of N fertilizer. Compared with grazing by heifers, grazing by dairy cows resulted in higher N removal, but did not change the amounts of residual N.

Mowing vs. grazing: environmental N efficiency

The environmental efficiency (or rather inefficiency) of N use in herbage production was expressed as the ratio of the residual inorganic N in the soil at the end of the growing season and the total herbage yield (Lantinga and Groot, 1996); the lower this ratio, the more environmentally efficient is the herbage production. For the cutting experiment, NEL yields corrected for losses during the field period, at harvest and in conservation were used. According to Nevens and Reheul (1999), the observed NEL yields on the cut plots were decreased (Table 4) by 0·20. This resulted in values of 0·30 and 0·44 kg residual nitrate-N GJ^{-1} NEL for the 0 N and 400 N treatments respectively (Figure 8). For the grazing experiment these values were 0·87 and 2·42 kg residual nitrate-N GJ^{-1} NEL respectively. Restricting this study to scale of the grassland plot indicates that the environmental efficiency under grazing is three to six times lower than that under cutting.

However, cut grass still has to be fed to livestock. For both grazed and cut grassland, Figure 9 represents the ratio of total N output to N input as a measure of the global N use efficiency. For both systems, N input (N_{in}) is the amount of fertilizer N applied. For the grazed plots, N output (N_{out}) is the N translocation in live-weight gain of the grazing heifers. For the cut plots, initial N_{out} is the amount of N translocated in the harvested herbage (including a loss of 0·20 for field and conservation losses). Adjusted values of N_{out} for the cut swards were calculated for two scenarios.

In the first scenario, it was assumed that, for dairy cattle, on average 0·20 of the amount of the herbage N intake by animals is retained in net animal production

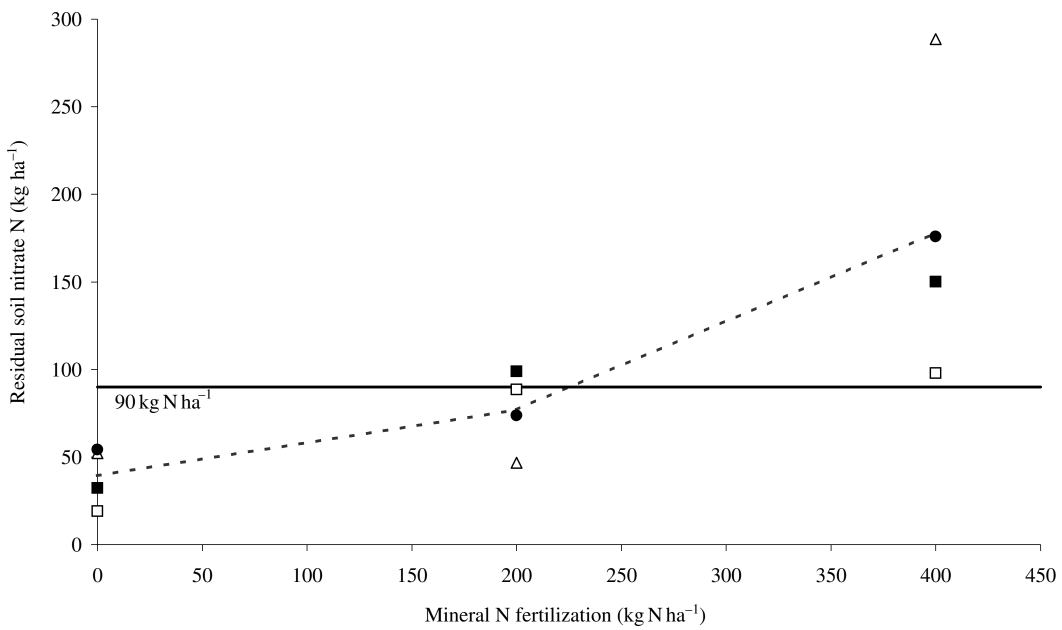

Figure 7 Residual soil nitrate-N (kg ha^{-1}; 0–90 cm) in the grazed swards after the growing seasons of 1996 (△), 1997 (■), 1998 (□) and 1999 (●).

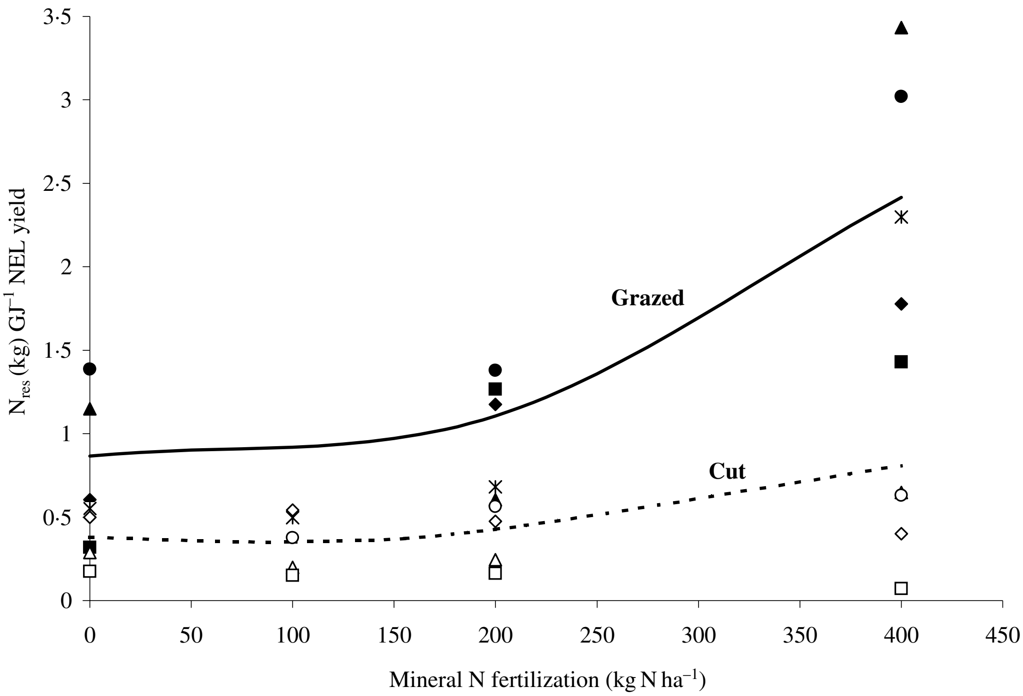

Figure 8 Relationship between inorganic N application and the amount of residual soil nitrate-N (0–90 cm) per GJ NEL yield on the cut (●) and grazed (○) grasslands.

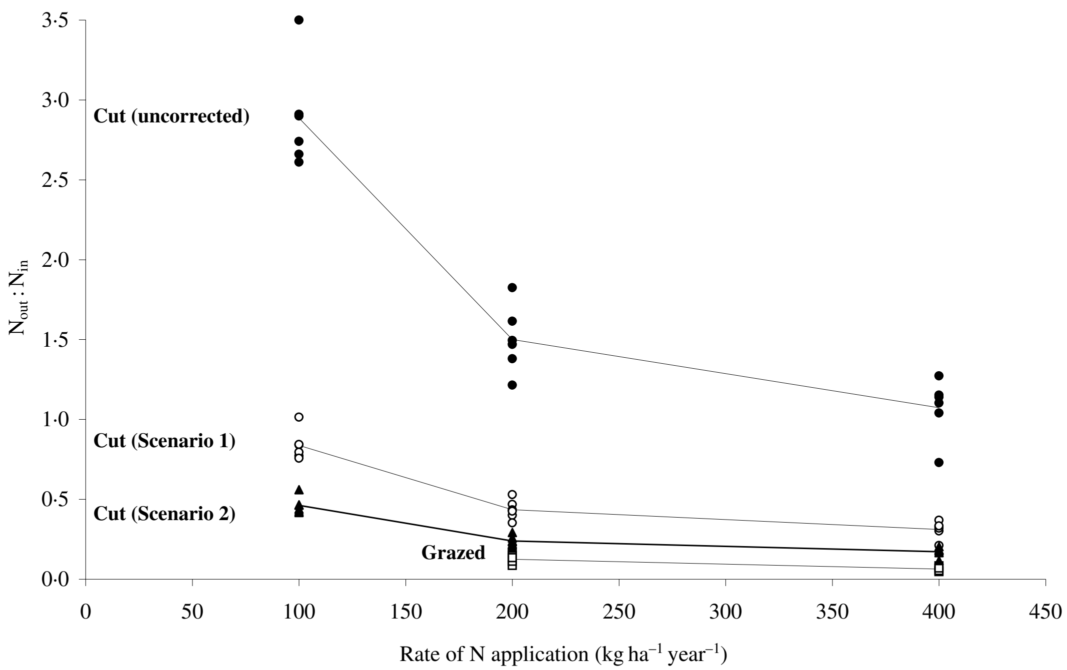

Figure 9 Ratio of N output to N input for the cut(●) and the grazed (○) swards. For the cut grasslands, N output was corrected for losses occurring after herbage intake by livestock (scenario 1: animal N use efficiency = 0·20; scenario 2: animal N use efficiency = 0·10).

(Goelema *et al.*, 1996; Van Bruchem *et al.*, 1996). The other 0·80 of N intake mainly ends up in manure. It was also assumed that 0·40 of the N in manure N will be used efficiently by the forage crop on which it is applied (Van Bruchem *et al.*, 1996) and 0·60 will be lost by volatilization, denitrification and leaching. The harvested forage crop returns to the animal compartment and the same loop was followed another three times. By then, there is a net N output (in animal production) of 29 kg N per 100 kg N initially taken up from harvested herbage. In this respect, the corrected N output of the cut grassland is 0·29 N_{out} for scenario 1.

In the second scenario, focused on growing animals, it is assumed that only 0·10 of the amount of the herbage N taken up is retained in net animal production (Watson and Foy, 2001). Other assumptions and the method were the same as before. This resulted in a net N output (in animal production) of 16 kg N per 100 kg N initially taken up from harvested herbage. In this respect, the corrected N output for growing animals is 0·16 N_{out}.

Using these corrected N_{out} values, the global efficiency of the cut grassland system is lower with scenario 1 values of 0·35 and 0·25 at N rates of 200 and 400 kg ha^{-1} yr^{-1} respectively (Figure 9). For scenario 2 these were 0·19 and 0·14. These values are still higher than on grazed grassland (0·12 and 0·06 at 200 N and 400 N respectively) but the overall N-use efficiency of both systems was remarkable (Figure 9).

Conclusions

On cut grassland, the economically optimal N fertilizer rate was at least 400 kg ha^{-1} yr^{-1}. This N application resulted in amounts of residual soil nitrate (0–90 cm) below the present or possibly revised legal limits of 90 and 70 kg nitrate-N ha^{-1} respectively. When cutting management aims at a substantial yield resulting from the white clover content in the sward, N fertilizer application rates should be limited to 100 kg ha^{-1} yr^{-1}.

On grassland grazed by heifers, it was not economically justified to apply more than 200 kg N ha^{-1} yr^{-1}. According to the present Flemish legal threshold on the amount of residual soil nitrate-N (90 kg ha^{-1}, 0–90 cm), this N rate was also the maximum from an environmental point of view. If the limit were revised to e.g. 70 kg N ha^{-1}, then the environmental optimum N rate would be about 150 kg N ha^{-1} yr^{-1}. Restricted to the grassland paddock scale, overall N-use efficiency (N_{out}:N_{in}) on cut plots was ten to twelve times higher than on grazed plots. However, the N_{out}:N_{in} ratio was only two to four times higher on the cut plots when feeding the cut grass to livestock was included.

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