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Agronomical and environmental evaluation of a long-term experiment with cattle slurry and supplemental inorganic N applications in silage maize

Frank Nevens [a,b,*], Dirk Reheul [a]

[a] *Department of Plant Production, Ghent University, Coupure Links 653, Ghent 9000, Belgium*
[b] *Centre for Agricultural and Resource Economics, Katholieke Universiteit Leuven, W. de Croylaan 42, Leuven 3001, Belgium*

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Abstract

During 19 years of research on silage maize grown a fertile sandy loam soil in Flanders, we compared the use of only inorganic nitrogen (S−) with a system of an annual application of dairy cattle slurry (S+, corresponding with an average rate of 180 kg N ha^{-1}) supplemented with inorganic fertilizer nitrogen. The objectives were to study the efficiency of slurry-N, to determine the economic optimum of additional fertilizer-N use and to relate this optimum with the local threshold on residual soil nitrate-N. During the last 5 years, the economically optimal fertilizer rates in the S− and the S+ system were centred around 150 and 90 kg N ha^{-1}, respectively. So, saving on fertilizer N amounted to about 60 kg N ha^{-1}. At these N rates, the risk for trespassing the local legal threshold value for residual soil nitrate-N content (90 kg ha^{-1}, 0–90 cm) was small (less than one out of ten seasons); economic and ecological optima of N fertilization concurred well. Meeting the standards of the EU nitrates directive and/or a doubled fertilizer N price would urge to decrease the applied amount of inorganic N by ca. 50 kg ha^{-1}, resulting in yield losses of about 5% on the studied sandy loam soil with an important content of total N (5300 kg ha^{-1}, 0–30 cm).

The ratio of N-fertilizer replacement to the total amount of applied slurry-N increased during the experimental period to an average level of 59% during the last 5 years.

Keywords: Cattle slurry; Economically optimal inorganic N rate; Residual soil nitrate-N; Slurry-N efficiency

1. Introduction

The efficiency of nitrogen (N) use in European silage maize (*Zea mays* L.) cropping has become a major issue of concern, as the crop is often negatively connoted to N-aspects of surface and groundwater quality (Gall Le et al., 1997; Schröder et al., 2000).

A number of specific characteristics of the maize cropping system frequently cause(d) a situation of overfertilization in European regions (Castillon, 2000):

(a) The long period during which the soil remains uncovered can mount up to 6 or 7 months, particularly when maize is cropped in a monoculture.
(b) The late sowing date (20 April–10 May) makes the silage maize predestined for slurry application. Often high slurry rates are applied, even exceeding

* Corresponding author. Tel.: +32-9-264-90-67; fax: +32-9-264-90-94.
E-mail address: frank.nevens@Ugent.be (F. Nevens).

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the crops actual needs. In contrast to other crops, maize tolerates such N overdosing without drawbacks as lodging or quality loss (Schröder and Dilz, 1987).

(c) The N provided by slurry is not fully taken into account and the mineral fertilizer inputs are not reduced accordingly (Angle et al., 1993; Schröder et al., 2000); prolonged use of slurry increases the mineralization capacity of soils and should justify lower N inputs.

(d) In a ley/arable rotation, large amounts of N are supplied by the cultivated grassland; this N credit decreases the need for N fertilizer use substantially (Nevens and Reheul, 2002) but is not always taken into account sufficiently.

(e) Slow plant growth and yellow whirls in spring due to cold spells are often misinterpreted as N deficiency and followed by supplemental N dressings.

Furthermore, silage maize takes up a relatively low amount of N (in Flanders ca. 225 kg N ha^{-1}; Herelixka et al., 2002), owing to the short growing season and the poor root extension.

As a result, compared to other crops, silage maize plots often show high amounts of post-harvest, residual mineral soil N (Guiot, 1981; Hofman et al., 1994; Lorenz, 1992) and hence higher over-winter nitrate leaching (Gall Le et al., 1997; Simon and Le Corre, 1988).

It should be highlighted that, besides negative environmental effects, high residual nitrate and leaching indicates economic inefficiency for producers (Karlen et al., 1998).

Two major strategies to tackle with high amounts of residual nitrate (and hence leaching risk) can be applied.

A first strategy is curative: catch crops sown after maize harvest or undersowed companion crops can capture residual N. However, due to the late harvest date of silage maize, N uptake by catch crops can be rather poor, particularly in cold autumns and winters (Aronsson and Torstensson, 1998; Castillon, 2000; Gall Le et al., 1997). Schröder et al. (1996) found that nitrate leaching under cover cropped plots at high N rates exceeded leaching under fallow plots at low N rates.

A second strategy is preventive and more reliable with respect to residual N. It focuses on a reserved N application and is based on the knowledge that the amount of residual soil N strongly depends on the applied N rates (Jokela and Randall, 1989), that the nitrate pool should at all times be kept as low as possible to avoid losses (Sharpley et al., 1998) and that the apparent nitrogen recovery of silage maize is low (Schröder, 1998). This N balancing remains a major challenge since a reduction of the maize crop N supply may well decrease the amount of residual N significantly (Dinnes et al., 2002) but at the same time it potentially reduces the crop yields.

In Flanders, silage maize comprises 114.000 ha, corresponding with 18% of the total utilised agricultural area and 29% of the arable land (NIS, 2001). In Flanders there is a high supply of nitrogen from animal production and high slurry doses are used in silage maize. However, the European nitrate guideline (Anonymous, 1991) provides that in vulnerable zones, the maximum amount of applied organic N should be limited to 170 kg N ha^{-1} per year. Therefore, it is beyond doubt that in the future, the Flemish silage maize production will have to optimize a fertilization management system with moderate slurry application rates.

The aim of our research was to look for the efficiency of slurry-N in silage maize and to determine the economic optimum of additional fertilizer-N. Moreover, we wanted to assess the risks on excessive nitrate leaching, using the amount of residual mineral soil N as an indicator.

The long duration of the experiment (19 years) also allowed us to monitor the evolution of the slurry-N availability and to consider the last 5 years as an equilibrium phase, allowing long-term conclusions and advice.

2. Materials and methods

2.1. Site characteristics

The fertilization experiment was carried out on a sandy loam soil of the experimental site of Ghent University at Melle (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 soil (0–30 cm) were 123, 566 and 311 g kg^{-1}, respectively. At the start of the experiment, the chemical soil fertility was “normal”, considering the local target values for sandy loam soils

Table 1
Top soil (0–30 cm) fertility parameters (expressed on air dry soil) at the start of the experiment (1983)

	P ($g\,kg^{-1}$)	K ($g\,kg^{-1}$)	Ca ($g\,kg^{-1}$)	pH—KCl
Value	0.17	0.14	1.71	6.47
Target range[a]	0.12–0.18	0.14–0.20	1.0–2.4	6.2–6.6

[a] According to local reference values for sandy loam soils (Vanongeval et al., 2000).

Table 2
Average rate of slurry application and the corresponding amounts of applied total N, P and K

Time period	Application rate ($Mg\,ha^{-1}$ per year)	Applied amount ($kg\,ha^{-1}$ per year)		
		N_{tot}	P	K
1983–1986	94.2	414	76	396
1987–2001	45.3	180	32	176
1997–2001	41.9	141	25	150

(Table 1). On an ammonium lactate extract of the soil, exchangeable K and Ca contents were determined spectrophotometrically, exchangeable P content was determined colorimetrically.

During the experimental period, the mean annual precipitation in Melle was 761 mm, the mean air temperature was 9.5 °C.

2.2. Fertilization treatments

The trial lasted from 1983 to 2001. On each of the four replicate blocks, a split-plot design was established, with presence (S+) or absence (S−) of an annual cattle slurry application as main plots (18 m × 30 m). If slurry was applied no additional P and K was applied. If no slurry was applied, inorganic P and K were applied at rates excluding deficits for the crop. According to Evers et al. (2000), K and P uptake of high yielding silage maize is 189 and 28 $kg\,ha^{-1}$ per year, respectively. We applied a minimum of 208 kg K and 32 $kg\,P\,ha^{-1}$ per year, using muriate of potash 33% K and triple super phosphate 18% P, respectively.

From 1983 to 1986 a moderate annual inorganic N rate (ca. 100 $kg\,ha^{-1}$) was applied on all the plots. From 1987 onwards, different inorganic N doses were imposed as subplots: 0, 50, 100, 150 or 200 $kg\,ha^{-1}$ (further indicated as 0N, 50N, 100N, 150N and 200N, respectively). Each subplot measured 6 m × 9 m (gross). The used inorganic N fertilizer was calcium ammonium nitrate (CAN, 27% N); it was always applied in spring, ca. 2 days before sowing. The inorganic N rate treatments were maintained on the same plots for the entire experimental period.

To determine the amount of applied slurry, the tractor and the tank wagon were weighed before and after slurry spreading on each of the four blocks. The slurry was sampled from the tank wagon before each of the four spreading tours; on a bulked sample we determined total N, P and K content (in duplicate). The average amounts of applied nutrients are summarized in Table 2. On average, 49% of the total slurry N was NH_4–N. We add that the slurry rates were high from 1983 to 1987 (on average 124 $Mg\,ha^{-1}$ per year, corresponding with 545 $kg\,N\,ha^{-1}$ per year) but from 1987 onwards, the annual application rate was severely decreased, to a level far more consistent with agronomic requirements (<250 $kg\,N\,ha^{-1}$ per year; Chambers et al., 2000). Also autumn applications were abandoned, taking into account their negative effect on N use efficiency (Kolenbrander, 1981a; Schröder et al., 1993) and the high risks on nitrate pollution.

Slurry was collected from a cubicle stall after mixing and applied by broadcast spreading from a trailed vacuum spread tank. Subsequent incorporation of the slurry into the soil (with a cultivator) followed immediately, i.e. within 2 h after the spreading. Regarding ammonia volatilisation losses, this technique of immediate incorporation had proved to be very effective (Dobbelaere, 1992). Measurements on the experimental plot during the spring of 1996 showed that immediate slurry incorporation with a cultivator decreased the ammonia-volatilization losses by 88%, without immediate incorporation, 13% of the total applied N volatized within the first 24 h; applying immediate incorporation reduced this share to 1.6% (Vermoesen, 1999).

2.3. Crop data and measurements

Silage maize (*Z. mays* L.) was grown in 17 out of the 19 considered seasons; in 1990 and 1993 fodder beet (*Beta vulgaris* L.) broke the maize monoculture.

At the end of the growing seasons, the crop yields were determined on the inner 6 m^2 (1.5 m × 4 m) of each subplot. The silage maize stalk with leaves and the ears were weighed separately. Subsequently, the leaves and stalks were chopped and dried (for 12 h at 80 °C); the ears were dried unchopped (for 12 h at 80 °C, followed by 4 h at 105 °C). The fodder beet roots and the beet tops were also weighed separately. Per subplot, we used a sample of 10 beet roots and the corresponding beet tops to determine the DM content. The beet tops were dried at 75 °C for 8 h. Representative root sectors, cut to particles of $\pm 1\,cm^3$, were dried at 75 °C for 8 h, subsequently at 105 °C for 4 h.

At each harvest, we determined the crop N content (Kjehldahl method) on samples bulked per treatment and we calculated the N uptake. Since bulked samples were used, no statistical analysis was carried out on these data.

For each growing season (from 1987 onwards), we fitted quadratic curves expressing the crop DM and N yield responses to the applied inorganic fertilizer N.

2.4. N fertilizer replacement value of the slurry (NFRV)

The nitrogen fertilizer replacement value (NFRV) (Bullock, 1992; Ziegler, 1994) is the amount of mineral fertilizer N that should be applied on S− plots to obtain a DM yield (or N yield) as high as on S+ plots without additional inorganic N application. The found NFRV provides an estimate of the amount of efficient N supplied to the crop by the slurry. The NFRV was determined by solving for *x* in the S− quadratic response curve, at *y* equalling the maize DM yield (or N yield) on S+ plots without inorganic N application. The ratio NFRV/slurry-N applied was then defined as the efficiency of the slurry-N (‘N_{eff}’).

2.5. The optimum rate of inorganic N

For S− as well as S+, the marginal DM yield response to applied inorganic N was determined by calculating the first derivative of the DM yield response curves (Bullock and Bullock, 1994). The economically optimum inorganic N fertilization (N_{opt}) was then determined as the N rate at which the yield response dropped to the cost:value ratio (CVR), defined as the ratio of the cost of 1 kg of mineral fertilizer N to the purchase price of 1 kg DM of silage maize (Neeteson and Wadman, 1987; Schlegel et al., 1996). According to Flemish local data, we applied a cost price of 0.75 Euro per kg of inorganic fertilizer N (spreading included) and a purchase price of 0.075 Euro for 1 kg of silage maize as well as fodder beet DM. This resulted in CVR = 10.

Cerrato and Blackmer (1990) and Bullock and Bullock (1994) found that compared to quadratic-plus-plateau response models, quadratic models could lead to an overestimation of N_{opt}. However, these authors considered a much wider range of N rates (up to 360 kg N ha^{-1} per year) and obtained response curves that levelled off at about 175 kg N ha^{-1} per year. Moreover, according to Cerrato and Blackmer (1990), possible overestimations of N_{opt} are most obvious at critical cost:value ratios below 10. For these reasons, we were quite confident in the use of quadratic DM and N yield response curves, also following Schlegel et al. (1996) and Vanotti and Bundy (1994a).

2.6. Residual soil nitrate-N

Although not an exact account for site-specific over-winter nitrate leaching (Rück and Stahr, 1996), soluble N remaining in the soil following harvest is an important indicator of the nitrate-N leaching potential (Jokela and Randall, 1989; Neeteson, 1995; Roth and Fox, 1990). In order to comply with the European nitrates directive (groundwater nitrate content <50 mg l^{-1}), current Flemish manure legislation allows an arbitrary maximum of 90 kg residual nitrate-N in the soil (0–90 cm; measured between 1 October and 15 November) (Declercq et al., 2001).

At the end of the growing seasons 1989–2000 (15 October 1989, 15 November 1990, 21 October 1991, 5 October 1992, 26 October 1993, 1 October 1994, 18 October 1995, 8 November 1996, 7 October 1997, 22 October 1998, 9 November 1999, 9 November 2000), the amount of residual soil nitrate-N (N_{res}) was determined. Three soil depths were sampled: A (0–30 cm), B (30–60 cm) and C (60–90 cm). For each treatment we bulked 12 soil cores (4 plots × 3 cores per plot) for each soil depth and we determined the nitrate content in double. We extracted the soil with a 1% $KAl(SO_4)_2$-solution; nitrate content of the extract was measured with a nitrate-specific electrode (Cottenie and Velghe, 1973; Hofman, 1983). Between sampling and analysis, the soil samples were deep-frozen and they were not dried before extraction.

We did not measure residual ammonium in the soil because it plays only a minor role in the leaching of nitrogen (Steenvoorden and Oosterom, 1976), owing to the low mobility of the ammonium cation in comparison to the nitrate anion (Legg and Meisinger, 1982; Whitehead, 1995). Moreover, the average winter (October–February) temperature in Melle (5.0 °C) is to low for considerable nitrification (oxidation of ammonium to nitrate) (Holland and During, 1977; Schmidt, 1982; Whitehead, 1995).

2.7. Statistical analysis

An analysis of variance was performed on the DM yield data, using the STATITCF-software package of the Institut National de la Recherche Agronomique (INRA, France).

3. Results

3.1. DM yields and calculated optimum inorganic N rates

Every season, the average crop DM yield on the S+ plots was higher than on the S− plots (data not shown). However, the positive yield effect of the slurry decreased with increasing additional inorganic N rate (there was always a significant S × N interaction, except for 1992; Table 3). Added for 15 years (1987–2001), the S+ plots outyielded the S− plots by 39, 14, 5 and 1% at annual inorganic N rates of 0, 50, 100 and 150 kg ha^{-1}, respectively (Fig. 1). At 200 kg N ha^{-1} per year, the slurry had a negative effect on DM yields: minus 3% on S+ plots. These observations illustrate that the slurry effect on the DM yields is a clear N contribution effect: when N supply is supra-optimal, no advantage of slurry was observed. Also Klausner et al. (1994) found that rates of 30–60 Mg dairy cattle manure ha^{-1} had no significant non-N-effects on maize DM yields.

If we assume that a period of at least 10 years is necessary for organic fertilization treatments to result into a steady state (Anderson and Peterson, 1973), we can consider the last 5 years of the trial as a period of equilibrium. During this lustrum, the average yield of the S− 0N treatment had dropped to 55.3% of the maximum observed yield of 18.2 Mg ha^{-1} per year (S− 200N). For the S− 50N, S− 100N and S− 150N plots, this was 81.0, 91.4 and 98.9%, respectively. When applying only slurry-N (S+ 0N), the yield level was 88.2% of the maximum. All the other S+ treatments had yields of more than 95% of the maximum.

Table 3
DM yield (Mg ha^{-1}) of silage maize or fodder beet (in bold), with (S+) or without (S−) slurry application, at different rates of inorganic N fertilization

Year	Inorganic N rate (kg ha^{-1})										Statistical significance		
	S+					S−					S	N	S × N
	0	50	100	150	200	0	50	100	150	200			
1987	10.6	12.9	14.3	14.6	15.0	7.9	11.2	13.4	14.4	15.4	NS	***	***
1988	14.0	16.1	17.2	17.3	17.4	10.7	14.8	16.9	17.0	17.0	**	***	***
1989	13.5	16.2	17.8	18.1	18.3	11.5	15.3	18.1	18.2	18.3	NS	***	*
1990	**23.9**	**25.3**	**26.0**	**26.6**	**27.2**	**19.8**	**23.2**	**25.4**	**27.4**	**29.5**	**NS**	***	***
1991	16.1	17.3	17.6	17.8	18.4	14.0	16.0	17.2	18.1	19.1	**	***	**
1992	6.4	9.5	12.5	15.1	16.0	3.0	6.6	9.5	11.6	16.9	*	***	NS
1993	**21.1**	**21.1**	**21.6**	**21.9**	**22.0**	**16.1**	**19.1**	**21.3**	**22.4**	**22.7**	**NS**	***	***
1994	15.8	16.2	15.7	15.7	16.2	11.3	14.3	15.3	15.8	16.1	*	***	***
1995	13.0	15.8	16.2	16.3	16.5	9.6	13.8	15.7	17.4	16.8	*	***	***
1996	14.7	15.0	15.5	15.4	14.8	10.6	13.6	14.4	15.4	15.6	*	***	***
1997	18.8	19.4	20.1	20.5	20.5	10.8	16.4	18.9	20.6	20.7	***	***	***
1998	13.9	15.5	15.9	16.5	16.5	9.2	12.8	14.8	15.6	16.0	**	***	***
1999	15.9	17.9	18.0	17.7	17.3	12.1	15.8	16.8	18.5	18.9	**	***	***
2000	15.5	17.2	17.2	17.4	16.9	9.3	14.8	16.1	17.6	17.4	*	***	***
2001	16.2	17.1	17.1	18.0	17.0	9.0	13.8	16.5	17.6	17.9	**	***	***
Average 1997–2001	16.0	17.4	17.7	18.0	17.6	10.1	14.7	16.6	18.0	18.2			

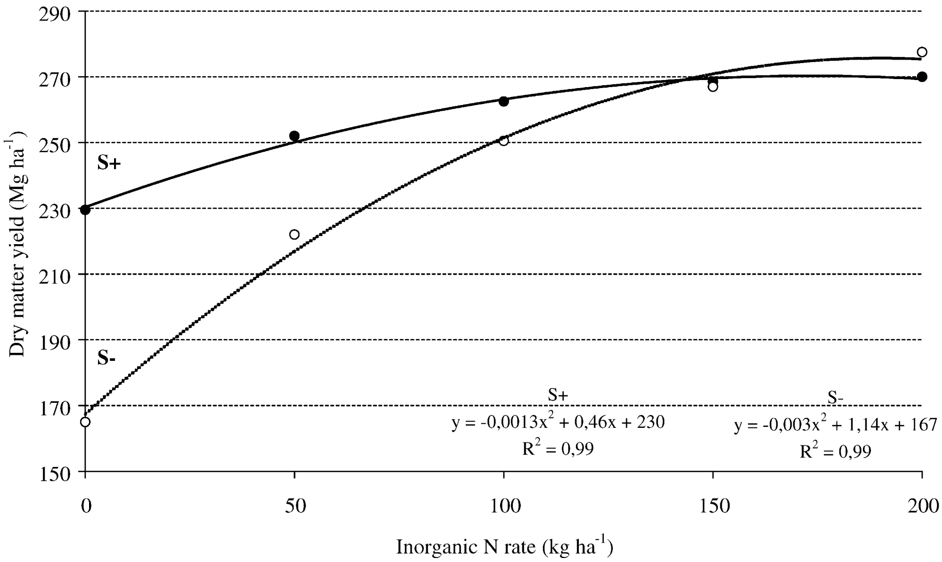

Fig. 1. Total dry matter yields on the plots with (S+) and without (S−) slurry application (accumulated yields from 1987 to 2001).

The calculated economically optimal inorganic N rates were always higher on the S− plots than on the S+ plots (Table 4). We found no clear relation between N_{opt} and the yield level and so we agree with Schlegel et al. (1996) and Vanotti and Bundy (1994a,b) that this optimum N rate is more site related than depending on changing growing conditions from year to year.

For silage maize on S− land, the average N_{opt} for the last five seasons was 154 kg ha^{-1}. Schlegel et al. (1996) found a comparable N_{opt} of 170 kg ha^{-1}, without slurry application and at CVR = 10.

On S+ plots, the average N_{opt} during the period 1997–2001 was 89 kg N ha^{-1}, concurring quite well with findings of Knittel and Lang (1992) and Magdoff and Amadon (1980), at comparable application rates of slurry application. At N_{opt}, the yields on the S− and S+ plots were quite comparable: 18.2 and 17.8 Mg DM ha^{-1} per year, respectively.

Fig. 2 illustrates that a potential increase of CVR (fertilizer N price/silage maize price) from current 10 to 20 (e.g. in case of doubled fertilizer N prices) would result in an N_{opt} decrease of only 19 kg N ha^{-1} on S− plots: from 154 to 135 kg N ha^{-1}. On S+ plots, the corresponding N_{opt} decrease would be 56 kg N ha^{-1} (from 89 to 33 kg N ha^{-1}). Although somewhat higher in combination with slurry application, the corresponding yield losses were still relatively small: 0.3 Mg ha^{-1} per year (−1.6%) and 0.8 Mg ha^{-1} per year (−4.7%) for S− and S+, respectively.

Table 4
Economically optimal inorganic N fertilization (N_{opt}; kg ha^{-1}) and corresponding DM yields (Y_{opt}; Mg ha^{-1}) on the plots without (S−) and with (S+) slurry application

		1987	1988	1989	**1990**	1991	1992	**1993**	1994	1995	1996	1997	1998	1999	2000	2001	Average m[a]	Average 5[b]
N_{opt}	S+	139	122	136	**161**	104	200	**0**	0	120	39	92	114	84	82	72	100	89
	S−	178	134	140	**200**	207	200	**163**	138	146	142	156	154	165	143	153	158	154
Y_{opt}	S+	14.8	17.4	18.3	**26.8**	17.7	16.2	**21.0**	16.0	16.7	15.1	20.0	16.3	18.0	17.3	17.3	17.0	17.8
	S−	15.1	17.4	18.5	**32.6**	19.0	16.4	**22.6**	16.0	17.1	15.4	20.8	15.9	18.7	17.7	17.9	17.4	18.2

Data in bold refer to fodder beet, others to silage maize.
[a] Average m = average for the maize seasons.
[b] Average 5 = average of the last 5 years, 1997–2001.

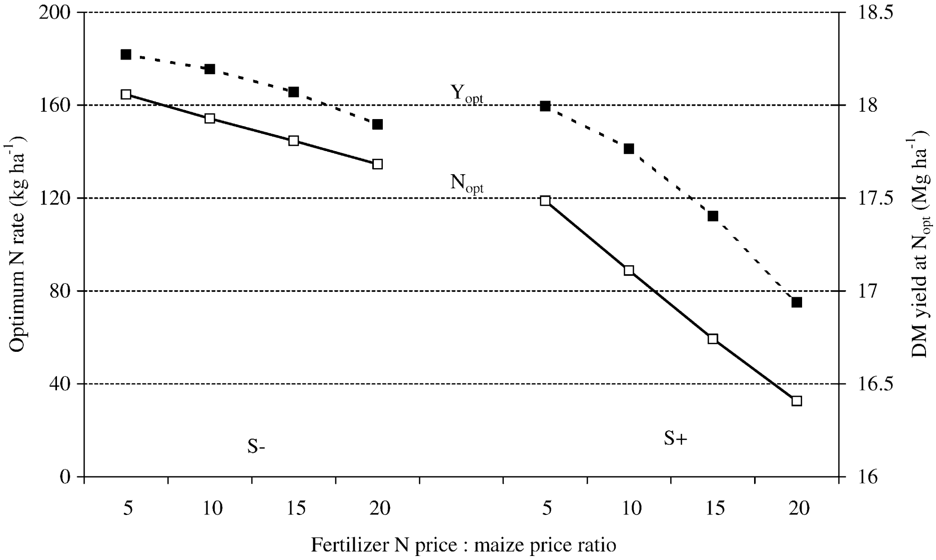

Fig. 2. Economic optimum of inorganic N rate (N_{opt}) and corresponding DM yields (Y_{opt}) on the plots with (S+) and without (S−) slurry application, in function of the fertilizer N price: maize price ratio.

3.2. N yields and N contents

Slurry application increased the N yields, most definitely at the lower inorganic N rates (Table 5): crops on S+ plots yielded 77, 47, 23, 14 and 8% more N than on S− plots, at an inorganic rate of 0, 50, 100, 150 and 200 kg ha^{-1}, respectively (Fig. 3). These relative differences are higher than the ones observed with DM yields (Fig. 1), indicating that the N content of S+ crops was higher than of S− crops. Fig. 4

Table 5
N yield (kg ha^{-1}) of silage maize or fodder beet (in bold), with (S+) or without (S−) slurry application, at different rates of inorganic N fertilization

Year	Inorganic N rate (kg ha^{-1})									
	S+					S−				
	0	50	100	150	200	0	50	100	150	200
1987	86	114	133	144	155	57	86	111	130	151
1988	128	142	196	204	211	80	114	165	181	198
1989	89	139	182	193	203	75	106	179	191	203
1990	**225**	**291**	**343**	**410**	**493**	**176**	**216**	**262**	**332**	**424**
1991	155	175	192	198	206	108	138	164	183	204
1992	42	60	81	107	134	21	39	54	70	130
1993	**211**	**228**	**263**	**307**	**350**	**125**	**164**	**200**	**226**	**245**
1994	163	192	184	193	206	91	143	168	180	181
1995	88	134	154	163	170	50	91	121	163	163
1996	173	183	195	202	192	86	127	165	186	187
1997	159	194	203	213	218	60	105	170	200	209
1998	118	147	166	183	181	55	87	131	151	170
1999	129	174	189	184	184	62	101	148	179	194
2000	137	172	184	196	180	50	95	134	170	186
2001	133	171	180	196	191	54	98	149	178	196
Average 1997–2001	135	172	184	195	191	56	97	146	176	191

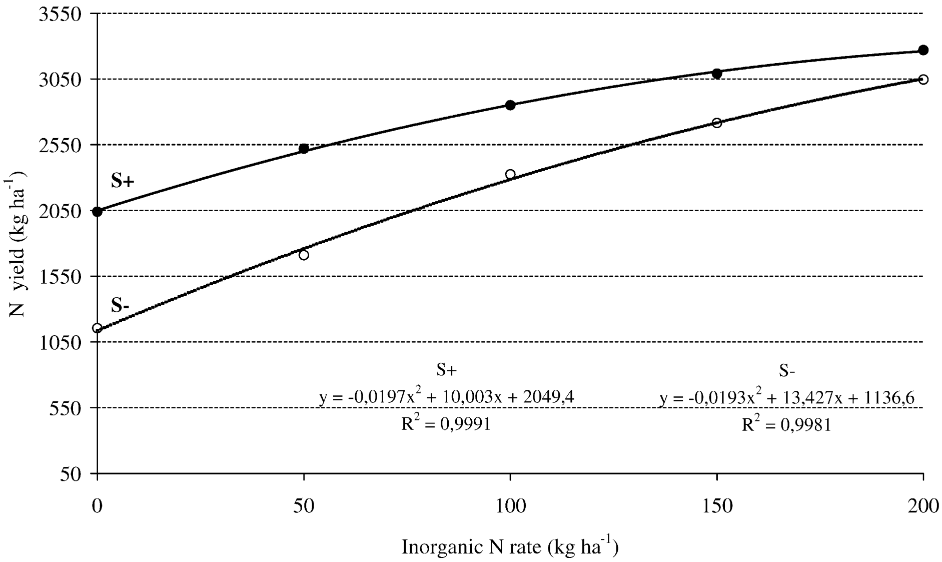

Fig. 3. Total N yields on the plots with (S+) and without (S−) slurry application (accumulated yields from 1987 to 2001).

confirms this N concentration effect, probably indicating the higher N availability on S+ plots (Killorn and Zourarakis, 1992). Fig. 4 also illustrates that fodder beet were outstanding in N uptake (up to a maximum of almost 500 kg ha^{-1}) as well as in N content of the dry matter.

3.3. *Slurry N efficiency*

The calculated efficiency of the slurry N (ratio of the N fertilizer replacement value to the amount of applied slurry N) is shown in Fig. 5. From 1987 to 1989 an average efficiency of only 15.8% was observed.

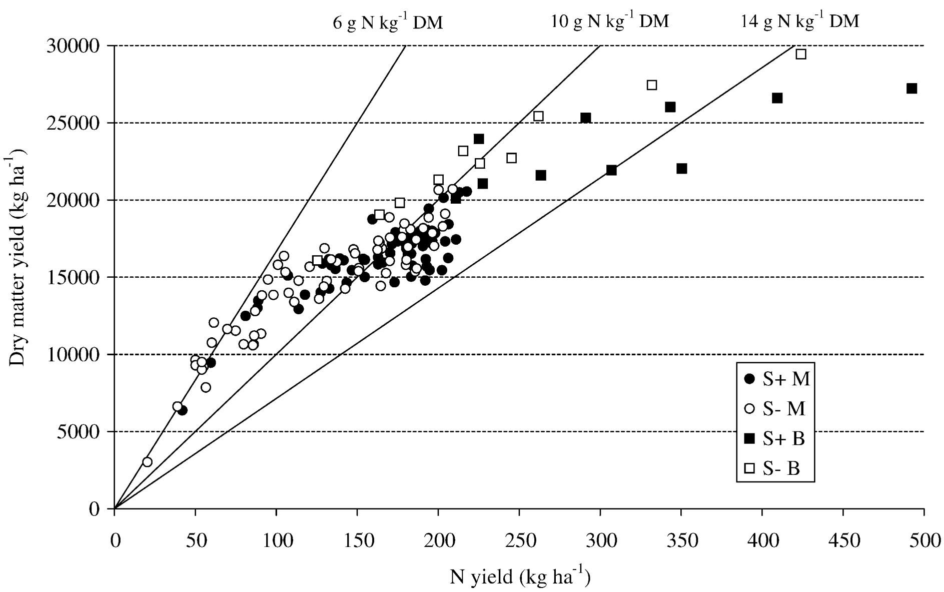

Fig. 4. Relationship between DM yield and N yield for silage maize (M) and fodder beet (B) on the plots with (S+) and without (S−) slurry application.

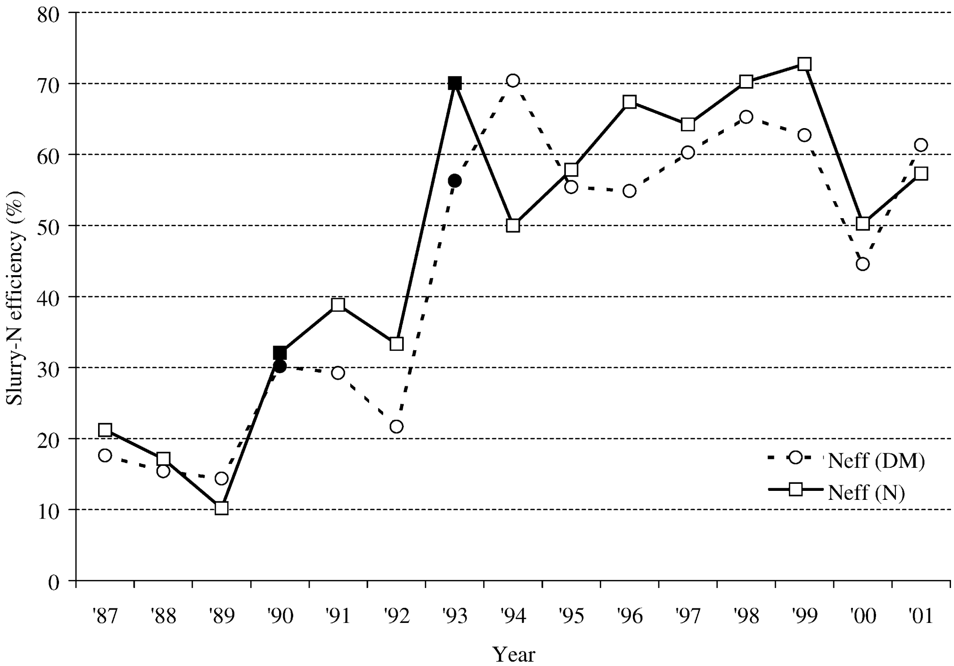

Fig. 5. Evolution of the efficiency of the slurry-N (N_{eff}) derived from dry matter (DM) or N yield (N) response curves to applied inorganic N.

During the fodder beet season of 1990 this efficiency increased to 30.2%, a value that kept up during the subsequent two silage maize seasons (on average 25.5%). Another fodder beet break in 1993 increased the efficiency to 56.3%. Higher use efficiency of cattle slurry-N in fodder beet was also observed by Claussen and Bohle (1980) and is due to the deeper rooting system and the longer growing season, resulting in a high N uptake (Fig. 4). In the maize years following the second beet break, the efficiency was again higher than in the seasons before the beet. During the last 5 years, N_{eff} had reached a level of on average 58.8%, concurring well with results of Bloc (1997), Knittel and Lang (1992), Kolenbrander (1981b). The N_{eff} calculated with NFRV based on N yields showed a comparable pattern (data not shown). The tendency of increasing fertilizer replacement value with long-term application was also demonstrated by Ziegler (1994) and is due to the increasing after-effect of previous applied manure rates. Indeed, decay series for organic N in manures may show a strong decrease (Klausner et al., 1994), the addition of the small after-effects of repeated manure applications add up to an important extra-supply of mineralized N, also for a long time after slurry application (Lund and Doss, 1980; Werner et al., 1985).

Another explanation for the increase of N_{eff} was the gradual optimization of slurry application throughout the experimental period: the incorporation was carried out more and more close to the spreading (from ±4 h to ±10 min after spreading) and the spreading was carried out more and more close to the sowing time (from ±40 to ± 7days).

Moreover, we observed a remarkable positive effect of fodder beet: N_{eff} was considerably higher in the fodder beet years (1990 and 1993) but also during the following maize years. Obviously also a crop rotation effect was in play.

3.4. Residual soil nitrate N

The amounts of residual soil nitrate following the fodder beet were always low (<50 kg N ha^{-1}, 0–90 cm), regardless of the amount of applied fertilizer N. This confirms that a fodder beet crop is very suitable to scavenge the soil, leaving hardly any N unused in the soil profile (Guiot, 1981; Nevens and Reheul, 2002).

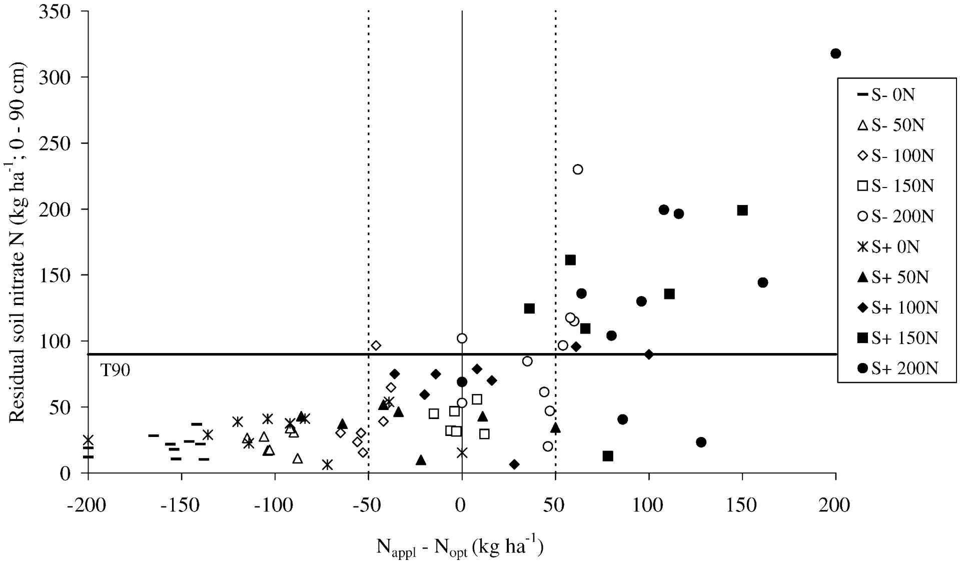

Fig. 6. Residual amounts of soil nitrate-N in relation to the difference between applied (N_{appl}) and optimum (N_{opt}) inorganic N rate, on the plots with (S+) and without (S−) slurry application. T90 = the Flemish legal threshold value.

In Fig. 6, the amounts of post-maize-harvest residual soil nitrate-N are presented. Instead of putting N_{res} in function of amounts of applied N, we related it to the difference between the applied inorganic N rate and the calculated economically optimal inorganic N rate (N_{opt}).

Within the zone of N_{opt} +50 and N_{opt} −50, the average amount of N_{res} on S+ and S− plots was 62 and 54 kg ha^{-1}, respectively. This indicates that applying N_{opt} for optimal financial return, meets quite well with the current Flemish 'ecological' threshold on N_{res} (90 kg ha^{-1}). A comparable conclusion was drawn by Schlegel et al. (1996). In contrast with Roth and Fox (1990), we found no substantial difference in N_{res} on S+ and on S− plots, both in the N rate range of N_{opt} ± 50.

It is well known that for fixed rates of a fertilization system, the amounts of residual soil nitrate-N strongly depend on seasonal weather characteristics, influencing soil N mineralization, crop N uptake and denitrification losses (Wantulla et al., 1988).

When a threshold value for N_{res} is available, the riskyness of a system to result in excessive nitrate leaching can be assessed by the breakthrough probability, based on N_{res} values of several years (Acutis et al., 2000). It turns out that the risk of trespassing the current Flemish threshold value of 90 kg N ha^{-1} within the N rate range of N_{opt} −50 to N_{opt} +50 was small (9%). Applying a N rate exceeding N_{opt} by 50–100 kg N ha^{-1} or by more than 100 kg N ha^{-1} resulted in a breakthrough probability of 77 and 88%, respectively. So, our findings concur with Roth and Fox (1990) that residual NO_3-N strongly increased when the input of mineral fertilizer N trespassed the N_{opt} level and with ten Berge et al. (2002), indicating that when the applied N rate exceeds the critical rate, residual soil N increases to more than 100 kg mineral N ha^{-1} (0–60 cm).

Should the Flemish threshold value be revised from 90 to e.g. 60 kg N ha^{-1}, the breakthrough probability in the N_{opt} ± 50 range would increase to 40%. In that case and assuming unchanged management, N rates of 50 kg ha^{-1} below the economical optimum would be necessary in order to be reasonably safe concerning N_{res}. According to the response curves of the last 5 years, this would mean a yield loss of 6.6 and 4.2% for S− and S+ plots, respectively. Schröder et al. (1998) also found only limited effects on yields (−16%) when the applied N rate was 100 kg ha^{-1} below the economical optimum. One can imagine that an improved crop husbandry might decrease the yield gap between ecological and economical optima, e.g. slurry

N placement, conditional post emergence N dressings and winter cover crops (Schröder et al., 1993).

4. Conclusions

Applying dairy cattle slurry at a moderate rate (on average 180 kg N ha^{-1} per year) and adding ca. 90 kg inorganic N ha^{-1} per year resulted in an economical optimum fertilization for silage maize on the studied Flemish sandy loam soil. At this economical optimum, the current Flemish threshold value of 90 kg residual nitrate-N ha^{-1} (0–90 cm) was not trespassed. Lowering the threshold to 60 kg ha^{-1} would urge to decrease the rate of inorganic N with 50 kg ha^{-1} below the economical optimum (39 instead of 89 kg N ha^{-1} per year); a doubled N fertilizer price would also lower the optimum, to 33 kg N ha^{-1} per year. Both measures would result in yield losses of no more than 5% on the studied sandy loam soil with an important stock of organic N.

During the experiment, the calculated N-efficiency of the slurry increased strongly: from about 20% in 1987 to about 60% in 2001.

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