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Nitrogen recovery and dry matter production of silage maize (*Zea mays* L.) as affected by subsurface band application of mineral nitrogen fertilizer

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Abstract

Fertilizers, including nitrogen (N), may be better available to crops when they are placed close to the crop's root system. Therefore, from 1991 to 1994 the effects of subsurface band application of mineral N fertilizer on the N recovery and dry matter (DM) yield of silage maize were studied in nine field experiments on sandy and clay soils.

In the early crop stages and especially in the clay soil experiments, banded N had a significant negative effect on the N uptake and DM yield compared to broadcast N, possibly due to salt damage. At final harvest, however, banding significantly increased the N uptake and DM yield in most of the experiments. The apparent N recovery increased by circa 20–25% (absolute).

The positive effects indicated that band application improved the efficiency of the N fertilizer. It could be calculated that banding allowed a reduction in the N rate of 20–30% without significant effects on the N uptake and DM yield of the silage maize. Benefits of banding were positively ($P<0.001$) related to the accumulated precipitation in the whole growing season.

When N was broadcast, soil mineral N measurements showed that, initially, N was preferably taken up from soil compartments near the maize row resulting in lateral gradients, that sometimes even persisted until final harvest. Band application resulted in strong lateral gradients in the early crop stages, decreasing during the growing season due to N uptake by the maize crop.

Root countings in two experiments showed that banding also seemed to affect root proliferation. Effects were, however, not consistent. Relatively more roots were found near the banded N in 1991 while in 1992 roots tended to avoid soil compartments with high N concentrations.

Keywords: band application, maize, nitrogen, recovery, root distribution

Introduction

Maize recovers soil nitrogen (N) less efficiently than cereals, beets and grass (Prins *et al.* 1988). This is partly due to N inputs exceeding crop demand, but also to certain crop characteristics such as an early cessation of N uptake and a poor root development. In the first two months after planting, root development is mainly restricted to soil compartments near the maize row (Barber & Kovar, 1991; Schröder *et al.*, 1996; Schröder *et al.*, 1997). This means that only a fraction of the present N can be exploited by the crop. This may be improved by band application of fertilizers, especially for those crops with a wide row spacing such as maize (Knittel, 1988). In several studies banded starter fertilizers, containing N and phosphorus (P), were found to have positive effects on maize yields (Touchton, 1988; Howard & Mullen, 1991; Jokela, 1992). Therefore, banding some N and P at planting is common in current practice.

In order to prevent crop damage due to high N concentrations, banding is generally restricted to circa 30 kg N ha $^{-1}$. However, positive effects of banding of mineral N fertilizer at planting, also have been mentioned at higher rates (Maddux *et al.* 1991; Maidl, 1990). Sawyer *et al.* (1991) and Schröder *et al.* (1997) demonstrated that maize yields increased when maize was planted close to the manure injection slots.

Band application of N fertilizers may thus increase the N recovery by crops. This paper presents the results of nine field experiments addressing the possible benefits of N banding in terms of N recovery and DM yield of silage maize.

Materials and Methods

Experimental sites

The experiments were carried out from 1991 to 1994 at three different sites in the Netherlands, at sandy soils in Haren (1991–1992) and Heino (1992–1994) and at a light clay soil in Lelystad (1991–1994). Site characteristics are given in Table 1. At Heino treatments returned to the same plot each year while at Haren and Lelystad the experiments were located on different fields.

Experimental design

The experiments were set up as a randomized block design with four replications. Treatments consisted of 4 to 6 N rates of mineral N fertilizer (calcium ammonium nitrate) and two methods of application. N rates included 0, 30 (not at Haren), 60, 90 (not at Haren 1991), 120 and 200 kg ha $^{-1}$. N was applied either as a broadcast dressing within two days after planting, or as a subsurface band in one operation together with the planting, 5 cm next to the maize row and 3–4 cm below it.

The plot size at Heino and Lelystad was 15 m × 6 m (8 rows) and 21 m × 6 m at Haren. The net area used for yield, soil mineral N and rooting measurements, was 13 m × 3 m and 19 m × 3 m (4 rows), respectively.

Table 1. Site characteristics (0–20 cm layer).

Site	Year	pH-KCl	Organic matter (%)	Pw[1] (mg l^{-1} P_2O_5)	K-HCl (mg 100 g^{-1} K_2O)	Mineral N[2] in April (kg ha^{-1})
Haren	1991	4.9	5.6	35	11	20
	1992	4.8	4.2	46	12	10
Heino	1992	5.7	4.3	67	15	49
	1993	–	–		–	31
	1994	–	–		–	40
Lelystad	1991	7.5	2.3	29	19	33
	1992	7.5	2.0	41	19	22
	1993	7.7	2.1	34	20	25
	1994	7.4	2.1	23	25	36

[1] Sissingh, 1971
[2] 0–30 cm at Heino and Lelystad

The Genstat 5 programme (Payne *et al.*, 1993) was used for the statistical analysis. For both the analysis of variance and the regression analysis of the effects of the N rate on the N uptake and DM yield, the control treatment (0N) was used for both application methods.

Crop husbandry

Silage maize (*Zea mays* L., cv. LG 2080 at Heino/Lelystad and cv. Pursan at Haren) was planted between April 20 and May 10 at a density of 100,000–115,000 plants per ha with a row spacing of 75 cm. The maize was harvested in September/October at a whole plant dry matter content of 30–35%. Weeds were successfully controlled with herbicides commonly used in practice. All plots received a broadcast P, K and Mg mineral fertilizer dressing at recommended levels. No manure was used during the experimental period.

Measurements

During the growing season the aboveground N uptake and the DM yield were determined five times (at the 5–6 and the 9–10 fully expanded leaves stage, at silking, milkripeness and maturity, referred to as H1-H5) at Haren and 2 times (at the 5–6 fully expanded leaves stage and at maturity, referred to as H1 and H5) at Heino and Lelystad. At H1 at Heino and Lelystad and H1-H4 at Haren, the aerial fresh material of a net area of 3 m^2 (Heino and Lelystad) or 4.5 m^2 (Haren) per plot was weighed. Subsequently, 10 plants were taken at random, chopped and a sample of 800 g was dried for 48 h at 105 °C. At maturity (H5) the DM yield of the maize was determined by weighing the fresh material from a net area of 39 m^2 (Heino and Lelystad) or 25.5 m^2 (Haren). Subsequently, the DM content was assessed by drying a sample of 800 g

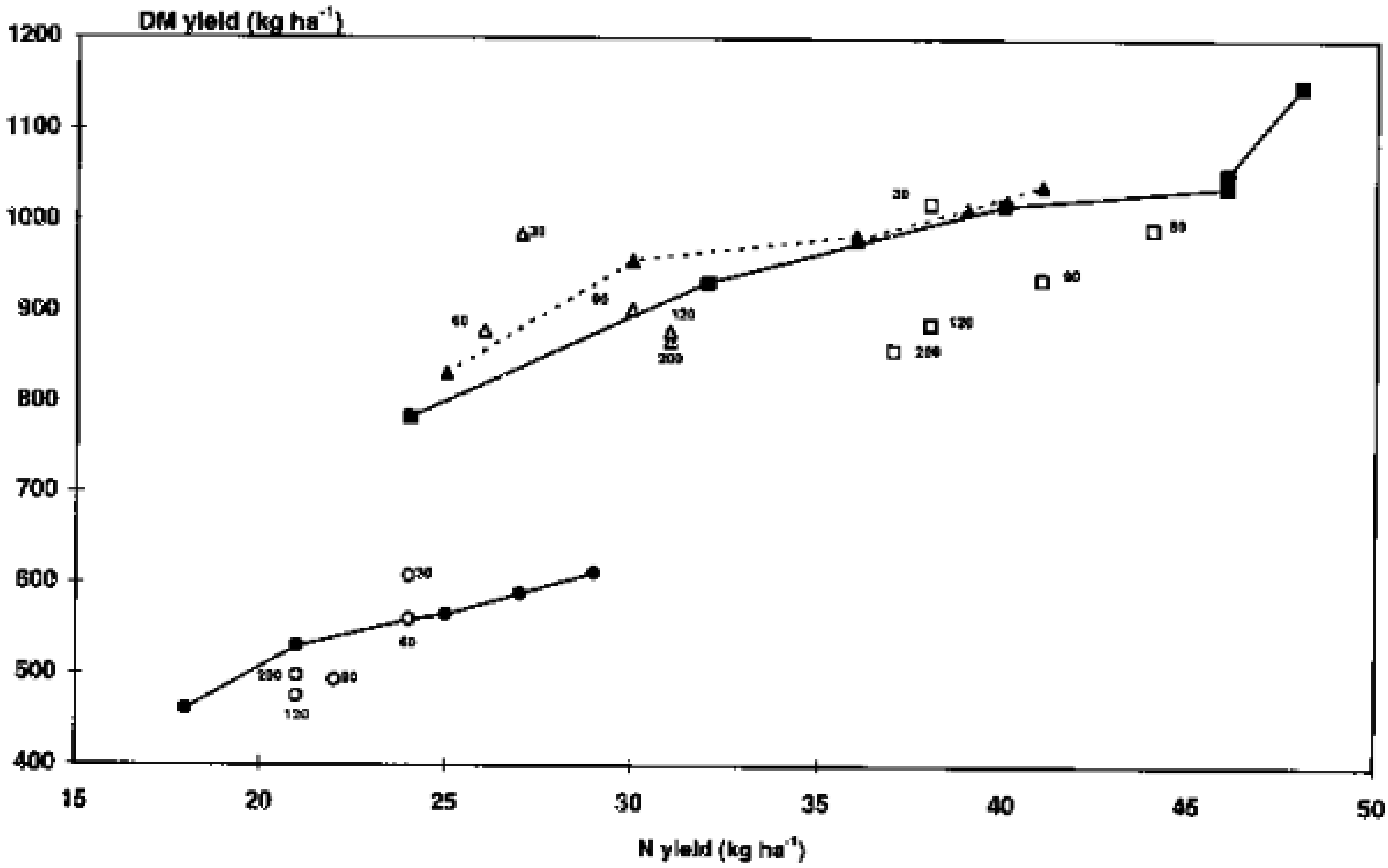


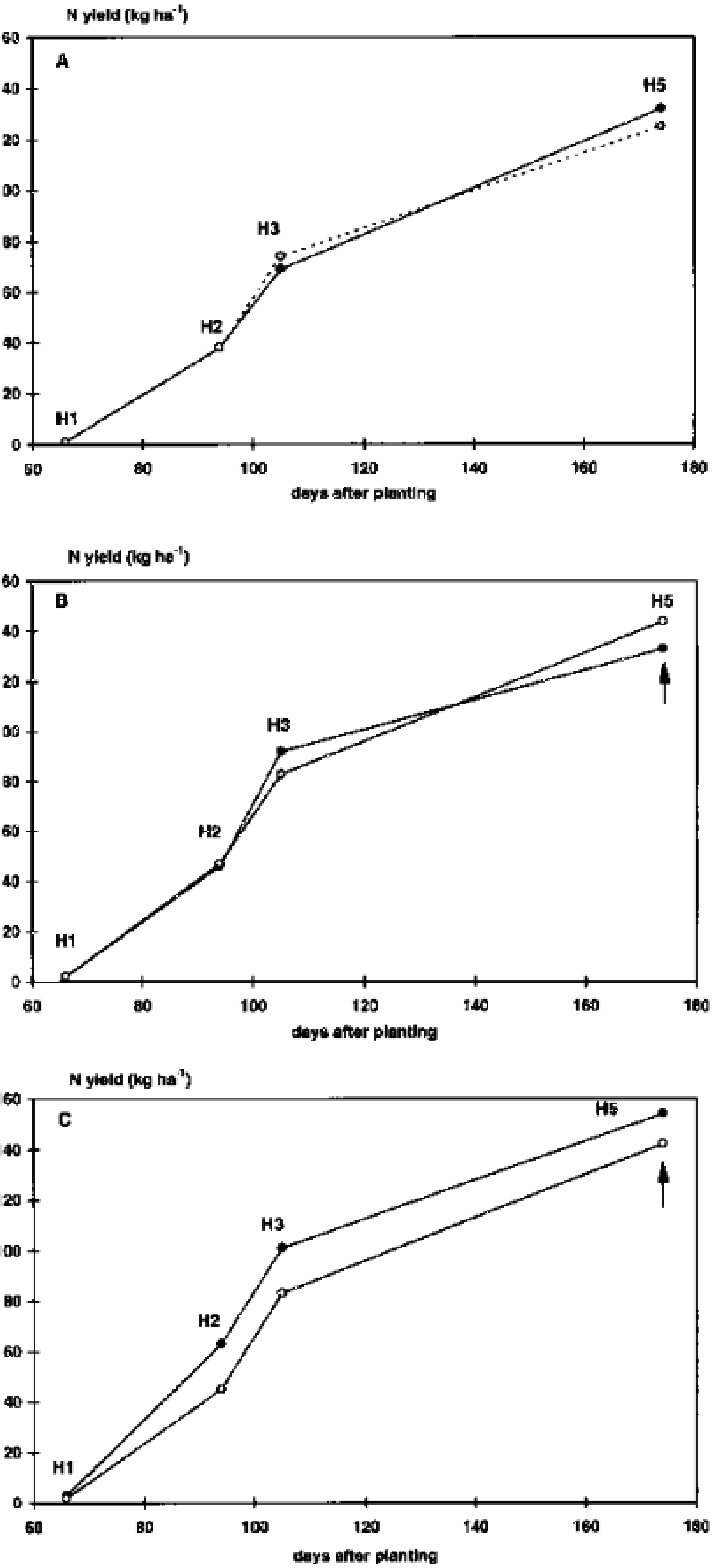
Figure 2. Relationship between the N uptake (kg ha^{-1}) and DM yield (kg ha^{-1}) of the silage maize at H1 as affected by the mineral N application method in 1991, 1992 and 1993 at the Lelystad site (▲ = broadcast, 1991; △ = band, 1991; ● = broadcast, 1992; ○ = band,1992; ■ = broadcast, 1993; □ = band, 1993; the figures besides banding data refer to the mineral N rate).

banded. Effects were most obvious in 1993. In the sandy soil experiments no effects of banding on NE were observed in the early stages (data not shown).

Figure 3 shows the effects of N banding on the N uptake at different growth stages (H1-H5) at the Haren site in 1991 and 1992 (no data were available for H4 in 1991). In 1991 significant effects of the application method were observed at the 120 and 200 kg ha^{-1} N rate at H5. At the 120 kg ha^{-1} N rate banding increased the N uptake while at the 200 kg ha^{-1} N rate, the inhibition in N uptake, observed in the early stages, persisted until the final harvest. Contrary to 1991, banding increased the N uptake at all N rates in 1992. The increase was already establised before silking at the 60 kg ha^{-1} N rate while at the higher N rates, 120 and 200 kg ha^{-1}, the difference in N uptake between the application methods increased until final harvest. The application method did not affect NE in either year at the intermediate harvests (data not shown).

N uptake and DM yield at final harvest

The application of N affected the N uptake and DM yield significantly in all experiments (Table 4 and 5). In eight out of nine experiments band application of mineral N significantly increased the N uptake at final harvest. A significant interaction was observed except for the experiments at Haren and Heino in 1992. N banding increased the ANR considerably (Table 6). Averaged over experimental years and N rates, the increase of ANR was 20% and 23% at the Heino and Lelystad sites, re-


N yield (kg ha^{-1})
A
H1
H2
H3
H5
0
20
40
60
80
100
120
140
160
60
80
100
120
140
160
180
days after planting
N yield (kg ha^{-1})
B
H1
H2
H3
H5
0
20
40
60
80
100
120
140
160
60
80
100
120
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160
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days after planting
N yield (kg ha^{-1})
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H1
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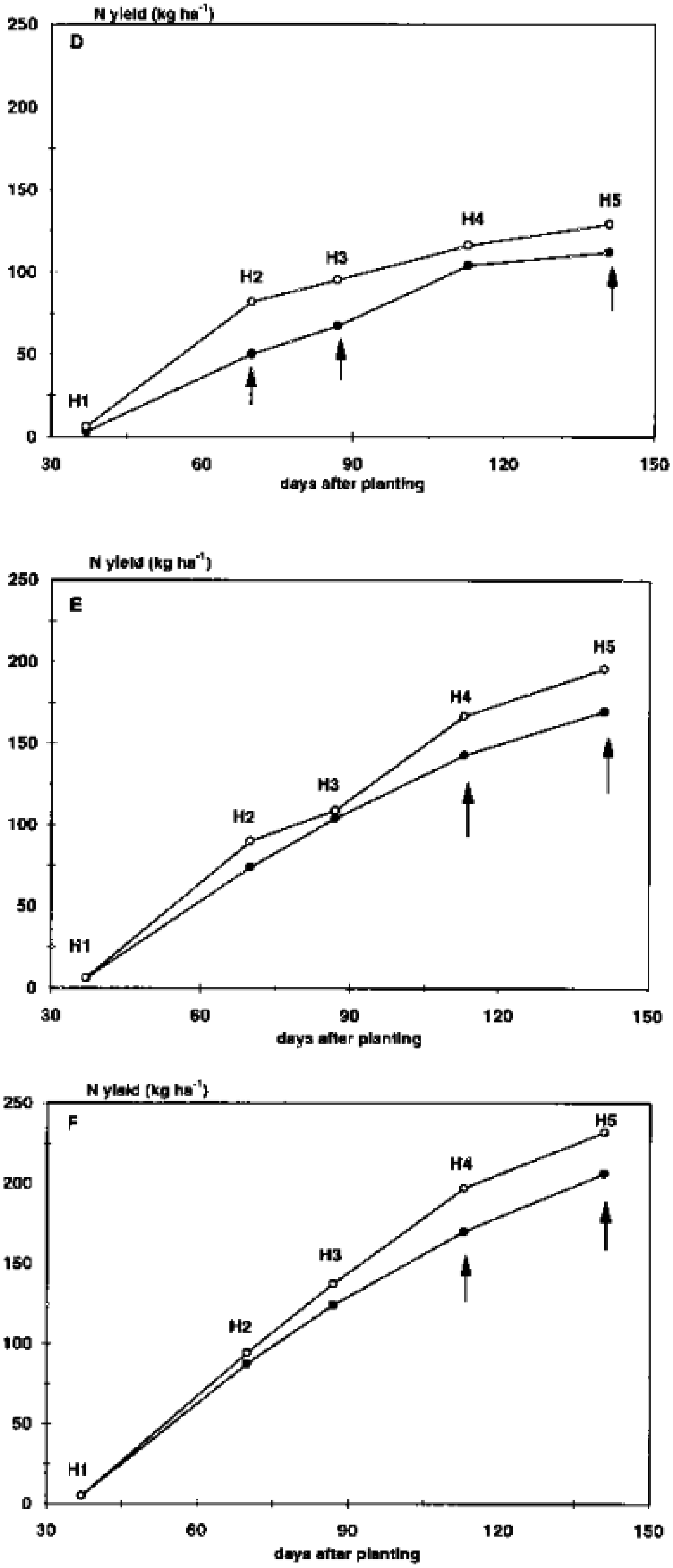

Figure 3. N accumulation of silage maize (kg ha^{-1}) as affected by the mineral N application method at N rates of 60, 120 and 200 kg ha^{-1} in 1991 (A, B and C, respectively) and 1992 (D, E and F, respectively) at the Haren site (● = broadcast appl., ○ = band appl.; arrows denote significance at $P<0.05$).

Table 4. N uptake of silage maize (kg ha^{-1}) at final harvest (H5) as affected by mineral N rate and application method.

Site	Year	Application method	N rate (kg per ha)						Significance (*P*-value)		
			0	30	60	90	120	200	Appl. Meth. (AM)	N rate (N)	AM x N
Haren	1991	broadcast	118		132	–	133	154	NS[1]	<0.001	NS
		band	-		125	–	144	142			
	1992	broadcast	80		112	154	170	206	0.043	<0.001	NS
		band	-		129	160	198	232			
Heino	1992	broadcast	101	116	132	148	151	182	<0.001	<0.001	NS
		band	-	114	146	162	170	192			
	1993	broadcast	81	105	126	138	143	165	<0.001	<0.001	<0.001
		band		119	156	162	165	170			
	1994	broadcast	52	67	93	112	131	177	<0.001	<0.001	<0.001
		band	-	67	116	137	163	190			
Lelystad	1991	broadcast	104	109	140	154	166	202	<0.001	<0.001	<0.001
		band		119	153	176	194	195			
	1992	broadcast	94	109	122	134	170	222	<0.001	<0.001	<0.001
		band		113	138	165	198	239			
	1993	broadcast	67	83	106	128	143	188	<0.001	<0.001	<0.001
		band		101	133	162	178	202			
	1994	broadcast	94	108	145	150	155	186	<0.001	<0.001	<0.024
		band		117	150	174	185	202			

[1] NS = not significant

spectively. The effects of banding on ANR were least at the 200 kg ha^{-1} N rate. At the Haren site in 1992 N banding also increased ANR, whereas in 1991 no significant effects of N banding were observed (data not shown).

Except for the experiments in 1991, the increase in N uptake due to N banding, significantly increased DM yield (Table 5). In four out of nine experiments a significant interaction was observed, absolute effects of N banding being smaller or even negative at the 200 kg ha^{-1} N rate. In none of the experiments NF at final harvest showed to be affected by the application method.

Efficiency of N banding

The positive effects of banding on the N uptake and DM yield, observed in most of the experiments, indicate that the efficiency of the N fertilizer was increased. To

Table 5. Dry matter yield of silage maize (ton ha^{-1}) at final harvest (H5) as affected by mineral N rate and method of application.

Site	Year	Application method	N rate (kg per ha) 0	30	60	90	120	200	Significance (*P*-value) Appl. Meth. (AM)	N rate (N)	AM x N
Haren	1991	broadcast	9.27		10.79	–	10.49	11.97	NS	<0.001	0.040
		band	-		10.35		11.62	10.89			
	1992	broadcast	10.81		13.30	15.49	16.13	16.89	0.011	<0.001	NS
		band	-		14.67	16.05	17.17	18.25			
Heino	1992	broadcast	10.82	12.48	12.38	12.62	12.83	13.95	0.050	<0.001	NS
		band		11.89	13.62	12.93	13.51	14.64			
	1993	broadcast	9.48	11.19	11.97	12.46	12.39	13.20	<0.001	<0.001	0.005
		band		12.18	13.12	13.22	13.69	12.95			
	1994	broadcast	7.32	9.24	11.13	12.23	12.83	14.01	<0.001	0.006	NS
		band		9.25	12.69	12.71	13.84	14.43			
Lelystad	1991	broadcast	12.25	12.96	14.88	15.55	16.28	16.70	NS	<0.001	NS
		band	-	13.62	15.26	15.88	16.19	15.95			
	1992	broadcast	10.97	12.81	14.33	15.59	18.13	19.99	<0.001	<0.001	0.004
		band	-	13.28	16.24	17.56	19.39	20.39			
	1993	broadcast	9.41	11.26	13.69	14.91	15.91	17.24	<0.001	<0.001	0.002
		band		13.45	15.48	16.09	16.65	17.27			
	1994	broadcast	11.80	12.76	14.42	14.76	14.77	15.93	0.003	<0.001	NS
		band		13.39	14.88	15.75	15.40	16.31			

[1] NS – not significant

quantify this effect RV was calculated based on the linear relationship between the mineral N rate and the N uptake of the silage maize (Table 7). RV values ranged from circa 70% to 80% (the experiment at the Haren site in 1991 was excluded be-

Table 6. Apparent N-recovery of silage maize (%) as affected by N application method and N rate at the Heino and Lelystad sites (average of whole experimental period).

Site	Period	Application method	N rate (kg ha^{-1}) 30	60	90	120	200
Heino	1992 1994	broadcast	60	65	60	53	48
		band	73	102	84	73	53
Lelystad	1991 1994	broadcast	40	63	58	58	55
		band	73	88	87	83	60

Table 7. Reduction value (RV) based on the linear relationship between mineral N rate and N uptake of the silage maize (regression analysis restricted to N rates ranging from 0 to 120 kg ha^{-1}).

Site	Year	RV (%)	VAF[1] (%)
Haren	1991	90	46
	1992	81	77
Heino	1992	78	90
	1993	69	88
	1994	74	96
Lelystad	1991	75	96
	1992	74	95
	1993	70	97
	1994	73	87

[1] Variance accounted for

cause of the low variance accounted for (VAF)). Average values of the sandy (excluding Haren 1991) and clay soil experiments were 76% and 73% , respectively.

To explain the observed variation in RV, a regression analysis was conducted relating RV to weather conditions and soil mineral N in spring. The experiment at Haren in 1991 was excluded for reasons mentioned before. The results show that benefits of banding were positively ($P<0.001$) related to accumulated precipitation in the whole growing season (Figure 4). In our experiments precipitation ranged from circa

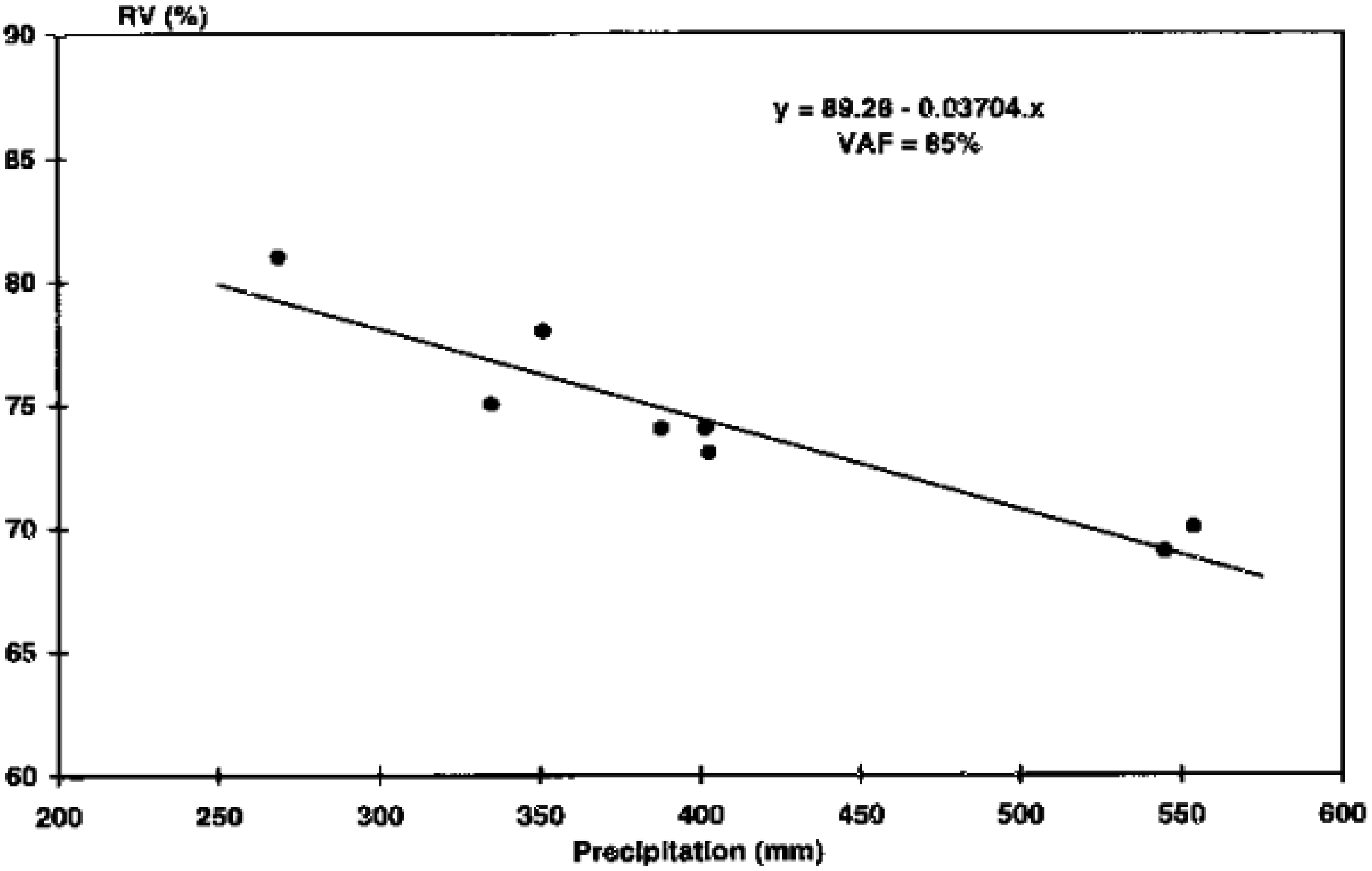

Figure 4. Relationship between accumulated precipitation in the period May-September (mm) and the reduction value (RV, %) (excluding the experiment at the Haren site in 1991).

270 mm to 550 mm which would have changed RV from circa 80% to 70%. VAF was not improved when average temperature or soil mineral N in spring were added to the regression model. However, variation in soil mineral N (30–70 kg $\mathrm{ha^{-1}}$) may have been too small to find any effects on RV.

Soil mineral N

At H1 in both 1991 and 1992 lateral distribution of soil mineral N was still quite homogeneous when N was applied as a broadcast dressing (Figure 5). When N was

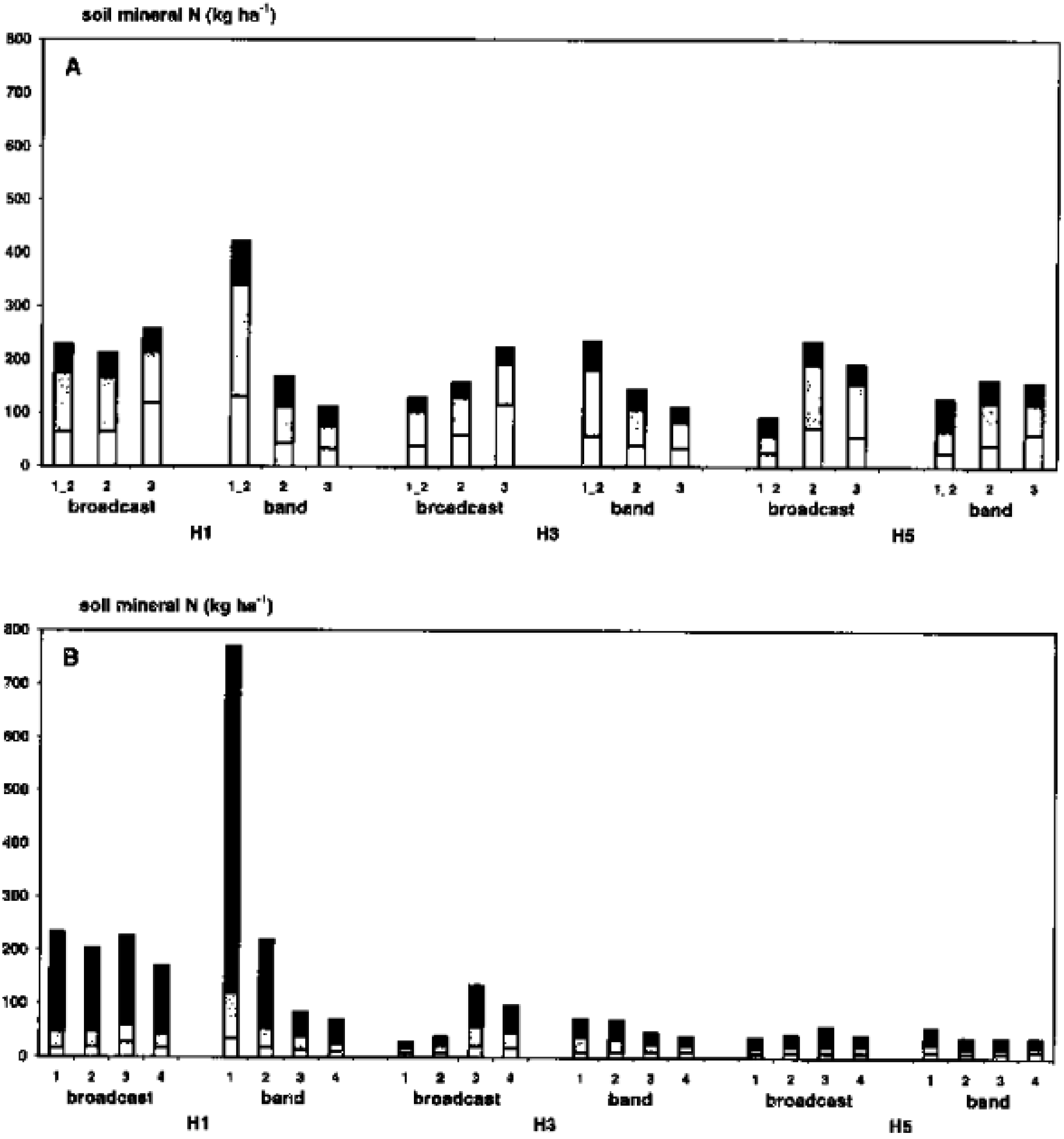

Figure 5. Lateral and vertical distribution of soil mineral N (kg $\mathrm{ha^{-1}}$) at the 200 kg $\mathrm{ha^{-1}}$ N rate as affected by mineral N application method at harvests H1, H3 and H5 in 1991 (A) and 1992 (B) (■ – 0–20 cm, ▨ – 20–40 cm, □ – 40–60 cm; for lateral positions P1-P4 see Figure 1; in 1991 measurements at P1 and P2 were pooled).

Table 8. Relative lateral root distribution (%) near the maize plant as affected by mineral N application method at the Haren site in 1991 and 1992 (side 1=side of band application).

Year	N rate (kg ha^{-1})	Application Method	Harvest stage					
			H1		H3		H5	
			Side 1	Side 2	Side 1	Side 2	Side 1	Side 2
1991	200	broadcast	41	59	48	52	43	57
		band	82	18	68	32	58	42
1992	90	broadcast	52	48			–	
		band	72	28		–		
	200	broadcast	50	50	45	55		
		band	38	62	31	69		

banded, N was preferably found near the maize row. At H3 soil mineral N was higher at greater distances from the maize row when N was broadcast while the opposite was found for the band application. At final harvest in 1991 a lateral gradient was still observed for the broadcast but not for the band application. In 1992 no lateral gradients were observed at final harvest at all.

Figure 5 also shows vertical distribution of soil mineral in the upper 0–60 cm layer for both application methods at the 200 kg N ha^{-1} rate. In 1991 relatively more N was found in the 20–40 and 40–60 cm layer than in 1992. This is probably due to high amounts of precipitation in the early stages in 1991 (Table 2) causing downward transport of mineral N. No obvious differences in vertical distribution were observed between application methods in any year.

Root measurements

In 1991 as well as in 1992 the application method affected the lateral root distribution near the maize row at the Haren site (Table 8). In 1991 at the 200 kg ha^{-1} N rate and in 1992 at the 90 kg ha^{-1} N rate relatively more roots were found on the side where the N was banded. At the 200 kg ha^{-1} N rate in 1992, however, the opposite was observed. In 1991 banding effects on root distribution decreased during the growing season at the 200 kg ha^{-1} N rate.

Discussion

Placement of fertilizers close to the roots may improve nutrient recovery by the maize crop. Therefore, between 1991 and 1994 the effects of subsurface banding mineral N fertilizer were studied in nine experiments on sandy and clay soils.

Results from our experiments showed that in the early crop stages (H1) and especially at the higher N rates, band application of N resulted in a growth inhibition. In the clay soil experiments the nitrogen efficiency (NE) tended also to be lower at H1 when N was banded indicating that factors other than N were more restrictive to crop growth at that moment. The observed growth inhibition may be due to high mineral N concentrations close to the maize roots causing salt damage. NH_3-toxicity due to the conversion of NH_4-N to NH_3 may also have played a role (Creamer & Fox, 1980). The enhancement of this conversion at higher soil pH-values might explain the stronger growth inhibition in the clay soil experiments compared to the sandy soil experiments. The growth inhibition could not well be related to weather conditions in the early crop stages as this occurred under favourable (1992 and 1993) as well as under unfavourable (1991) growing conditions.

Compared to the broadcast application, banding resulted in a higher N uptake and DM yield at final harvest in most of the experiments. So, the observed inhibition of crop growth in the early stages was reversed into a positive effect of banding on the N uptake and DM yield. Results from intermediate harvests at the Haren site in 1992 showed that at lower N rates this positive effect was established earlier in the growing season than at higher N rates. Possibly, a slower recuperation of crop growth may play a role since inhibitory effects in the early stages were stronger at higher N rates. This might also explain the observed interaction between the N rate and the application method, banding effects being smaller at higher N rates. However, this may also result from a higher N availability at higher N rates as positive effects of fertilizer placement are expected to be smaller at high levels of availability.

Band application increased the apparent N recovery (ANR) considerably. Similar results have been reported by Maddux *et al.* (1991), Maidl (1990) and Schröder *et al.* (1996). Sawyer *et al.* (1991) and Schröder *et al.* (1997) also found positive effects of band application of manure. It must be emphasized, however, that a better placement of P probably played an important role in the latter experiments.

The positive effects of band application may first result from a higher N availability as with banding most N is applied where rooting density is highest (Barber & Kovar, 1991; Schröder *et al.*, 1996). Furthermore, banding leads to a less intensive contact of soil and fertilizer which may reduce the risks of immobilization and denitrification (Mengel & Kirkby, 1978). For the same reason nitrification of ammoniacal N might be slower, as reported by Malhi & Nyborg (1985) and Wetselaar *et al.* (1972), thus reducing the risks of leaching when N is banded. However, this may also be due to the salt effect which does not allow any microbe, including nitrifying and denitrifying ones, to survive. Finally, apparent benefits of banding could have been partly caused by the poor availability of the non-incorporated broadcast N. Ammonia volatilization from the broadcast N may have been higher (Dilz, 1987) but also application depth might play a role since the broadcast N was applied superficially while the banded N was placed on a depth of circa 10 cm. Vertical distribution patterns of soil mineral N in our experiments did not give evidence for this, however, measurements were done in 20 cm layers. Probably, more detailed measurements are needed to rule this out.

The positive effects of banding indicated that the N fertilizer efficiency was improved. Based on the relationship between mineral N rate and N uptake of the silage maize the increase in efficiency was 20–30%. As NE was not affected by application method this means that N rates could be reduced with 20–30% without yield loss. A positive relationship ($P<0.001$) was found between accumulated precipitation in the whole growing season and banding efficiency. As under dry conditions soil mineral N is less diluted, N concentrations may have become too high for optimal crop growth resulting in a lower banding efficiency. This might be enhanced by a slower dispersal of the banded N in the soil as under dry conditions mineral N transport is reduced (De Willigen & Van Noordwijk, 1995).

Soil mineral N measurements showed, that when N was applied as a broadcast dressing, lateral gradients were observed especially in the period until silking indicating that, initially, N is preferably taken up from soil compartments near the maize row. This just has to be ascribed to higher rooting densities near the maize row as observed by Barber & Kovar (1991) and Schröder *et al.* (1996). Contrary to 1992, lateral gradients in 1991 persisted until final harvest probably due to a lower N uptake as compared to 1992. Similar results were obtained by Aufhammer *et al.* (1991).

Results of root countings showed conflicting results of banding on root distribution near the maize row. In 1991 and in 1992 at the 90 kg ha^{-1} N rate, relatively more roots were found at the side where the N was banded. Such proliferation effects were also found by Schröder *et al.* (1996). In 1992, however, roots seemed to avoid the banded side of maize plants. This may be due to differences in precipitation. In 1991 due to high precipitations, relatively more N was found in deeper layers resulting in lower N concentrations in the soil compartments where the root countings were done. In 1992, however, most N was found in the upper layer resulting in higher mineral N concentrations which might have inhibited root development in the soil compartments where N was banded.

Conclusions

Recovery of mineral N fertilizer by silage maize was improved by subsurface banding at planting compared to its broadcast application. N banding allowed a reduction of the fertilizer input by circa 20–30%, without loss of yield. However, to avoid salt damage dressings should not exceed 120 kg N ha^{-1}.

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References

Aufhammer, W., E. Kübler & H.W. Becker, 1991. Stickstoffaufnahme von und Stickstoffverlagerungspotential unter Maisbeständen. *Maïs-DMK* 4: 30–32.

Barber, S.A. & J.L. Kovar, 1991. Effect of tillage practice on maize root distribution. In: B.L. McMichel & H. Persson (Eds.), Plant roots and their environment. Elsevier, Amsterdam, pp. 402–409.

Böhm, W., 1979. Profile Wall Methods. In: W.D. Billings, F. Golley, O.L. Lange & J.S. Olson (Eds.), Ecological studies: Analysis and Synthesis. Springer-Verlag, Berlin-Heidelberg, pp. 48–59.

Cerrato, M.E. & A.M. Blackmer, 1990. Comparison of models for describing corn yield response to nitrogen fertilizer. *Agronomy Journal* 82: 138–143.

Creamer, F.L. & R.H. Fox, 1980. The toxicity of banded urea or diammoniumphosphate to corn as influenced by soil temperature, moisture and pH. *Soil Science Society of America* Journal 44: 296–300.

De Willigen, P. & M. Van Noordwijk, 1995. Model for interactions between water and nutrient uptake. In: P. Kabat, B. Marshall, B.J. van den Broek, J. Vos & H. van Keulen (Eds.), Modelling and parametrization of the soil -plant-atmosphere system: a comparison of potato growth models. Wageningen Pers, Wageningen, pp. 135–153.

Dilz, K. (1987). Efficiency of uptake and utilization of fertilizer nitrogen by plants. In: D.S. Jenkinson & K.A. Smith (Eds). Nitrogen efficiency in agricultural soils. Elseviers Applied Science, London, pp. 1–25.

Howard, D.D. & M.D. Mullen, 1991. Evaluation of in-furrow and banded starter N P K nutrient combinations for no-tillage corn production. *Journal of Fertilizer Issues* 8(2): 34–39.

Jokela, W.E., 1992. Effect of starter fertilizer on corn silage yields on medium and high fertility soils. *Journal Production Agricultural* 5: 233–237.

Knittel, H., 1988. Placement of solid fertilizers in agricultural crops: a review. Proceedings of The Fertilizer Society of London No 273, 35 pp.

Maddux, L.D., C.W. Raczkowski, D.E. Kissel & P.L. Barnes, 1991. Broadcast and subsurface banded urea nitrogen in urea ammonium nitrate applied to corn. *Soil Science Society of America Journal* 55: 264–267.

Maidl, F.X., 1990. Pflanzenbauliche Aspekte einer gezielten N-versorgung und verbesserten N-Ausnutzung. *Bayerisches Landwirtschaftliches Jahrbuch* 2: 77–87.

Malhi, S.S. & M. Nyborg, 1985. Methods of placement for increasing the efficiency of N fertilizers applied in the fall. *Agronomy Journal* 77: 27–32.

Mengel, K. & E.A. Kirkby, 1978. Principles of Plant Nutrition. International Potash Institute, Bern, 593 pp.

Payne, R.W., P.W. Lane, P.G.N. Digby, S.A. Harding, P.K. Leech, G.W. Morgan, A.D. Todd, R. Thompson, G. Tunnicliffe Wilson, S.J. Welham & R.P. White, 1993. Genstat 5 Release 3 Reference Manual, Clarendon Press, Oxford, 796 pp.

Prins, W.H., K. Dilz & J.J. Neeteson, 1988. Current recommendations for nitrogen fertilisation within the E.E.C. in relation to nitrate leaching. Proceedings of The Fertiliser Society of London No. 276, 27 pp.

Sawyer, J.E., M.A. Schmitt, R.G. Hoeft, J.C. Siemens & D.H. Vanderholm, 1991. Corn production associated with liquid beef manure application methods. *Journal Production Agricultural* 3: 335–344.

Schröder, J.J., J. Groenwold & T. Zaharieva, 1996. Soil mineral nitrogen availability to young maize plants as related to root length density distribution and fertilizer application method. *Netherlands Journal of Agricultural Science* 44: 209–225.

Schröder, J.J., L. ten Holte & G. Brouwer, 1997. Response of silage maize to placement of cattle slurry. *Netherlands Journal of Agricultural Science* 45: 249–261.

Sissingh, H.A., 1971. Analytical technique of the Pw method used for the assessment of the phosphate status of arable soils in The Netherlands. *Plant and Soil* 34: 483–446.

Touchton, J.T., 1988. Starter fertilizer combinations for corn growth on soil high in residual P. *Journal of Fertilizer Issues* 5: 126–130.

Wetselaar, R., J.B. Passioura & B.R. Singh, 1972. Consequences of banding nitrogen fertilizers in soil. I. Effect on nitrification. *Plant and Soil* 36, 159–175.