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Crop rotation versus monoculture; yield, N yield and ear fraction of silage maize at different levels of mineral N fertilization

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Abstract

Dry matter (DM) yields, N yields, ear fractions and economically optimum N fertilizer rates for silage maize were determined in monoculture and in rotational cropping on a sandy loam soil in Flanders. Rotationally cropped silage maize resulted in higher DM yields, higher N yields and higher ear fractions. These positive effects decreased with increasing mineral N fertilization. With both rotational cropping and monoculture, economically optimum maize yields were obtained with a lower N fertilizer input than was the case for the physically optimum yields, and the optimum N rate was likely to decrease further if the future N fertilizer use will be restricted by levies or higher fertilizer prices. The gradual increase in yield potential of silage maize resulting from plant breeding was expressed better and was exploited in a more efficient way when maize was grown in rotation than when grown in monoculture.

Keywords: crop rotation, monoculture, dry matter yield, economically optimum N fertilizer rate, nitrogen yield, silage maize.

Introduction

Narrow crop rotations, particularly monoculture, often result in yield decreases (Power & Follett, 1987; Peterson & Varvel, 1989a, b, c). Long-term studies have shown that crop rotations with or without legumes are essential to maintain high production levels (Mitchell *et al.*, 1991). Yet, the practice of monoculture became popular when it was evident that mineral fertilizers and pesticides could be used as a substitute for crop rotation (Crookston *et al.*, 1991; Bullock, 1992). Although mineral fertilizers and pesticides generally only partly compensate for the yield depression associated with monoculture (Bullock, 1992; Aref & Wander, 1998), economical considerations have made this practice a widespread phenomenon. Maize (*Zea mays* L.), which generally is considered a relatively 'self-tolerant' crop, is a classical example of this evolution. In Flanders, about 180,000 ha – more than 20% of the arable land – are cropped with silage maize, most of which is grown in monoculture. In this paper the term *monoculture* is used to refer to the repeated cropping of a sole crop on the same piece of land.

Crop rotation affects yields, amongst other things, through its effects on plant nutrient availability (Baldock & Musgrave, 1980), particularly that of nitrogen (Bolton *et al.*, 1976). Bullock (1992) defined the nitrogen (N) part of the total beneficial rotation effect as the 'N-contribution effect'. Many researchers have reported a decreasing beneficial effect of crop rotation on maize yield with increasing N fertilization. A summary of seventeen references, illustrating this general observation, is presented in Figure 1. The results originate from Adams *et al.* (1970), Anderson *et al.* (1997), Baldock & Musgrave (1980), Baldock *et al.* (1981), Bolton *et al.* (1976), Copeland & Crookston (1992), Johnson (1927), Lory *et al.* (1995a), Peterson & Varvel (1989c), Raimbault & Vynn (1991), Riedell *et al.* (1998), Robinson (1966), Scholte (1987), Shrader *et al.* (1966), Singer & Cox (1998), Stecker *et al.* (1995) and Van Doren *et al.* (1976). These findings imply that the level of applied fertilizer N should always be taken into account when interpreting crop rotation effects.

Beneficial effects of crop rotation also occur with a high N supply (Crookston *et al.*, 1991) or when maize follows non-leguminous crops (Porter *et al.*, 1997). In the latter case the N contribution is generally low (Schmid *et al.*, 1959), except for a possible carry- over of N from crop residues. Baldock *et al.* (1981) defined the effect of all contributions other than N as the 'additional rotation effect'. This effect, which is observed best at optimal or supra-optimal N fertilizer levels, is defined as the difference between the observed – or predicted – maximum yields of maize in monoculture and those of maize in rotation.

The beneficial, non-N effects of a rotation have been ascribed to improvements in soil structure (Dick & Van Doren, 1985; Weisskopf *et al.*, 1995), soil moisture con-

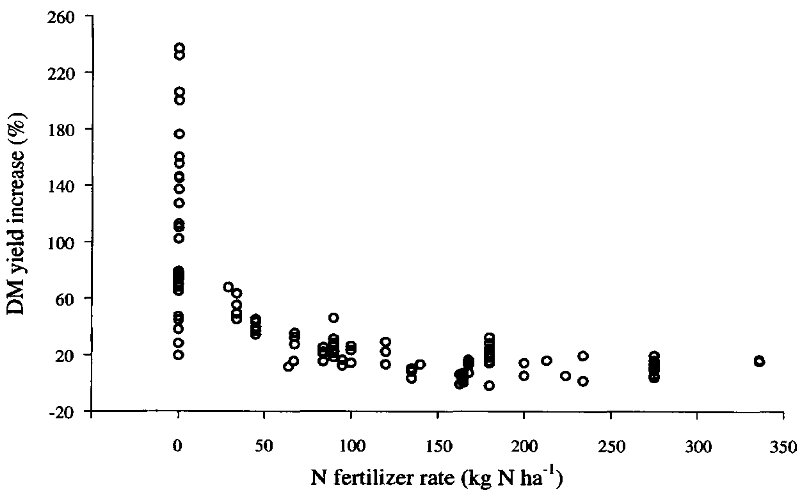

Figure 1. Relative yield increase of maize grown in rotation compared with maize in monoculture at different rates of mineral N fertilizer (summary of 17 references).

tent (Adams *et al.*, 1970), soil microbial or fungal populations and plant disease pressure (Huiskamp & Lamers, 1992; Johnson *et al.*, 1992; Scholte, 1987; Turco *et al.*, 1990; Van Zeeland *et al.*, 1999), root vigour (Nickel *et al.*, 1995) and weed infestation or allelopathic effects (Miller, 1996). The real complex of causal agents is often unknown, and the observed effect is sometimes referred to as a 'mysterious rotation effect' (Bullock, 1992). Crookston *et al.* (1988) assumed that the rotation effect is not only due to some positive after-effect of the previous alternate crop(s). It seems that – besides that some crops have a growth stimulatory effect on any subsequent crop – the growth of any crop is adversely affected if preceded by the same crop. Many crops that precede maize result in a substantial positive rotation effect, but grasses closely related to maize are relatively ineffective (Porter *et al.*, 1997).

Maize generally is more productive when grown in rotation than in monoculture, but maize itself can also have a positive effect in nullifying a monoculture effect of e.g. soybean (Peterson & Varvel, 1989b) or another cereal (Vez, 1975).

As reported by Huiskamp & Lamers (1992), Scholte (1987) and Van Zeeland *et al.* (1999), maize following leguminous or non-leguminous crops can show improved root growth and root vigour, which can have consequences for the uptake of nutrients and water. So crop rotation could be a potentially useful practice for obtaining comparable or even higher maize yields with less fertilizer N. This is reflected by different yield responses of maize in monoculture and maize grown in rotation to N fertilization (Lory *et al.*, 1995b; Omay *et al.*, 1998; Peterson & Varvel, 1989c; Varvel & Peterson, 1990).

Olsen *et al.* (1970) found that the total amount of (residual) soil nitrate was directly related to the rate of N application and to the frequency of maize in a rotation. If N requirements are lower when crops are grown in rotation, the potential risk of nitrate leaching during winter may be reduced. To attain the EU nitrate standard (Anon., 1980), recent Flemish legislation restricted the use of N fertilizer (Anon., 2000). In order to meet with present or tighter future restrictions on N fertilizer use, the re-introduction of formerly well-known agronomic practices like crop rotation may need reconsideration.

The aim of our research was to compare silage maize grown in rotation with forage crops, with silage maize grown in monoculture. We determined the dry matter (DM) yields, the N yields, the ear fractions and the N requirements in both practices. The trial included permanent grassland plots, plots permanently cropped with maize, and plots cropped for three years with maize alternated by three years of a grazed grass ley. For the effects of the grassland period on yields and N requirements of the arable crops in the ley–arable crop rotation see Nevens & Reheul (2001a). For the comparison of the yields of the three-year ley with those of the permanent grassland see Nevens & Reheul (2001b).

In the present paper, we focus on the comparison maize-in-monoculture versus maize in rotation with another arable crop. Both practices were compared for permanently cropped land and for the three-year cropping periods of the ley–arable crop rotation.

Materials and methods

Field experiment

In 1966, a crop rotation trial was established on a sandy loam soil at the experimental farm of Gent University at Melle (50°59' N, 03°49' E; 11 m above sea level). The clay (<2 μm), silt (2–20 μm), fine sand (20–200 μm) and coarse sand (200–2000 μm) contents of this soil were 86, 116, 758 and 40 g kg^{-1}, respectively.

The trial was of a 4 x 4 Latin square design. Individual plot size was 750 m^2. The following four rotation treatments were established (Table 1):

LA1: ley–arable crop rotation, starting with three years of grass ley (TG) followed by three years of forage crops (TA), etc.

LA2: arable crop–ley rotation, starting with three years of forage crops (TA) followed by three years of grass ley (TG), etc.

PA: permanently cropped with forage crops.

PG: permanent grassland.

In 1981, the plots with treatments TA and PA were split into two subplots. One subplot was assigned to the treatment *silage maize in monoculture* (MM), the other to *rotational silage maize* (MR), i.e., silage maize with fodder beet (*Beta vulgaris* subsp. *vulgaris* L.) and field bean (*Vicia faba* L.) (Table 1).

The effects of the three years grazed ley on the subsequent crops are presented in detail in Nevens & Reheul (2001a). In the present paper, we particularly focus on the growing seasons in the period 1987–2000 when it was possible to compare maize in monoculture (MM) with simultaneously grown rotational maize (MR) (Table 1). The comparison was made for the permanently cropped plots (PA) and for the ley–arable crop rotation plots following the three years old ley (TA). In 1988, 1991, 1997 and 2000, the rotationally grown maize followed fodder beet, in 1993 the maize followed

Table 1. Crop sequences for the different rotation treatments during the period 1987–2000.

Main treatment[1]	Sub-treatment[2]	Year													
		'87	'88	'89	'90	'91	'92	'93	'94	'95	'96	'97	'98	'99	'00
LA1	MR	G[3]	G	G	Bv	M	Vf	G	G	G	Bv	M	M	G	G
	MM	G	G	G	M	M	M	G	G	G	M	M	M	G	G
LA2	MR	Bv	M	Vf	G	G	G	M	M	Vf	G	G	G	Bv	M
	MM	M	M	M	G	G	G	M	M	M	G	G	G	M	M
PA	MR	Bv	M	Vf	Bv	M	Vf	M	Bv	Vf	Bv	M	M	Bv	M
	MM	M	M	M	M	M	M	M	M	M	M	M	M	M	M
PG		G	G	G	G	G	G	G	G	G	G	G	G	G	G

[1] LA = ley–arable crop rotation; PA = permanently cropped; PG = permanent grassland.
[2] MR = crop rotation; MM = silage maize in monoculture.
[3] G = grass ley; M = silage maize; Bv = fodder beet; Vf = field bean.

field bean but only on the permanently cropped plots (PA). Until 1989, a fixed amount of mineral N of 180 kg ha^{-1} was applied on the crop plots, except for field bean, which received 25 kg N ha^{-1}.

From 1990 onwards, sub-subplots with N fertilizer rates of 0, 75 and 180 kg mineral N ha^{-1} (ammonium nitrate 27% N) were established on each arable-crop treatment (PA MR, PA MM, TA MR and TA MM). These N treatments were maintained throughout the subsequent seasons. A sub-subplot measured 45 m^2; net plot size was 20 m^2. When field bean was grown, a single N rate of 25 kg ha^{-1} was applied. We always used top silage maize cultivars, chosen from the Belgian national variety list. Weeds were controlled with appropriate herbicides. The number of maize plants per plot was the same for all treatments. When fodder beet was harvested, all leaves were removed from the plots. This was also done with the haulm and the pods of the field bean. For more agronomic data see Table 2.

Crop data collected

At harvesting, fresh weights of maize leaves + stalks and of ears were determined

Table 2. Agronomic data for the forage crops grown during the period 1987–2000.

Year	Sowing date	Cultivar	kg P_2O_5[1] ha^{-1}	kg K_2O[1] ha^{-1}	Harvest date
Silage maize					
1987	23/04	Amazone	150	300	19/10
1988	20/04	Gracia	150	300	07/10
1989	02/05	Frida, Baron	150	300	26/09
1990	24/04	Aladin	150	300	11/09
1991	25/04	Frida	150	300	11/09
1992	24/04	Aladin	150	300	23/09
1993	23/04	Kalif	150	200	21/09
1994	28/04	Banguy	100	300	19/09
1995	27/04	Banguy	100	400	12/09
1996	18/04	LG2243	100	300	08/10
1997	23/04	LG2243	100	300	23/09
1998	08/05	Elita	100	300	25/09
1999	04/05	LG2243	100	300	16/09
2000	02/05	LG2243	100	300	25/09
Fodder beet					
1987	15/04	Kyro	150	200	25/10
1990	02/04	Bolero	150	200	07/11
1996	09/04	Apex	100	400	17/10
1999	29/04	Cesar	100	400	19/10
Field bean					
1989	13/03	Albatros	100	150	24/07
1992	10/03	Caspar	150	200	08/08
1995	23/03	Mixture	150	200	09/08

[1] Only mineral fertilizer was applied. P_2O_5 as triple superphosphate (43% P); K_2O as muriate of potash (40% K).

separately per net sub-subplot. Leaves and stalks were chopped and dried for 12 hours at 80 °C. The complete maize ears were dried for 12 hours at 80 °C, followed by 4 hours at 105 °C. The ear weights were used to calculate the ear fraction of the DM yield, which is a measure of the feed energy of the silage maize. The total N content (Kjehldahl method) of the separate plant fractions was determined for samples bulked per treatment. The total N yield by the silage maize of each treatment was calculated by multiplying the DM yield by the corresponding N content.

For each growing season we fitted quadratic curves expressing the relation between DM yield and applied fertilizer N. The marginal yield responses were determined by the first derivative of these response curves (Bullock & Bullock, 1994). The economically optimum N fertilizer rate (N_{opt}) was calculated as the N rate at which the yield response dropped to a critical value of P (Neeteson & Wadman, 1987), where P is the cost:value ratio, defined as the ratio of the cost of 1 kg fertilizer N and the purchase price of 1 kg DM silage maize. According to local data, we used a cost price of € 0.75 per kg fertilizer N and a purchase price of € 0.075 for 1 kg DM silage maize. This resulted in a critical P of 10. Considering possible future price increases of fertilizer N, N_{opt} was also determined for an arbitrary critical P of 30.

The N Fertilizer Replacement Value (NFRV) of the field bean (1992) for the subsequent maize crop (1993) was determined. This NFRV is defined as the amount of fertilizer N required on the maize in monoculture to reach a DM yield equal to that of the unfertilized maize crop following the field bean (Paré *et al.*, 1993). In the same way, we calculated the NFRV based on N yield curves. We also determined NFRV for a preceding fodder beet crop using DM yield as well as N yield response curves.

Yields of fodder beet and field bean were determined (i) to calculate total arable crop yields and (ii) to compare 11 years (1990–2000) of cumulative yields of the crop rotation and of the silage maize grown in monoculture, both on the PA and the TA plots.

Climatological data

Precipitation and air temperatures during the growing seasons were recorded at the meteorological station of Melle. The accumulated effective temperature for silage maize was determined according to Bloc & Gouet (1977), by adding the positive daily values of:

$$T_{effective} = \frac{(T_{max} + T_{min})}{2} - T_{base}$$

where
T_{max} = maximum daily temperature (°C),
T_{min} = minimum daily temperature (°C),
T_{base} = 6 °C.

The data are summarized in Figures 2 and 3 together with the 39-year averages over the period 1962–2000.

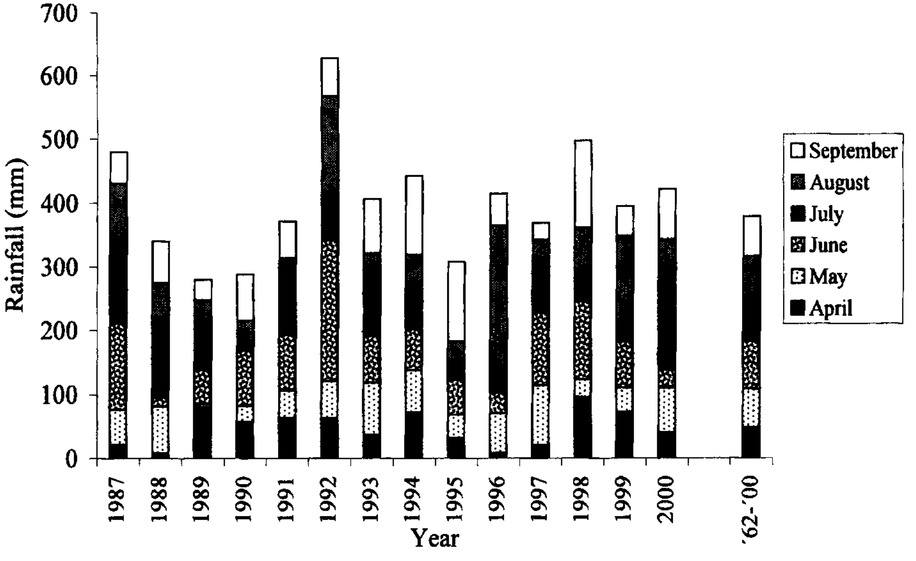

Figure 2 Rainfall at the experimental site of Melle during the growing seasons of 1987 to 2000 compared with the 39-year average over the period 1962–2000.

The 1988 and 1991 growing seasons were not favourable for silage maize. In 1988, spring was very dry. In 1991, spring was bleak. The seasons of 1993, 1997 and 2000 were 'normal', favouring a good crop growth and a high production.

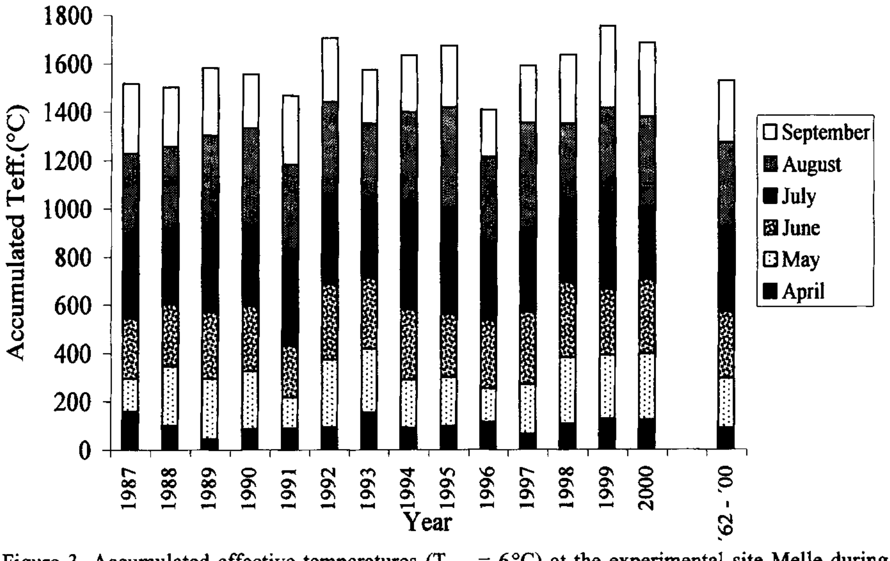

Figure 3. Accumulated effective temperatures (T_{base} = 6 °C) at the experimental site Melle during the growing seasons of 1987 to 2000 compared with the 39-year average over the period 1962–2000.

Results

Silage maize yields and yield responses to N fertilization

The yields of the maize grown in monoculture and the rotationally grown maize are presented in Table 3. On the *permanently cropped plots* in 1991, 1993 and 1997, a significant positive DM yield effect was recorded for the maize grown rotationally (MR) compared with the maize in monoculture (MM). The effect decreased with increasing N fertilizer level: it dropped from 17–42% following fodder beet, and from 143% following field bean at treatments without N fertilization, to 0–2% and –3%, respectively, at 180 kg N ha^{-1}. At this N fertilizer level, in 1988 no significant yield differences between MM and MR silage maize were found either.

The significant interaction between type of rotation and fertilizer N rate (Table 3)

Table 3. Yields (t DM ha^{-1}) of silage maize grown in rotation (MR) or in monoculture (MM), in the second year after a three years old grass ley (TA) or on permanently cropped plots (PA), as affected by N fertilizer rate.

Year	Treat-ment	Previous crop[1]	TA			PA		
			N rate[2]			N rate[2]		
			0	75	180	0	75	180
1988	MR	Bv			18.8			18.8
	MM				18.8			18.3
1991	MR	Bv	15.8 c[3]	17.9 a	18.6 a	9.3 d	14.8 b	18.9 a
	MM		13.0 d	17.0 b	19.0 a	6.6 e	12.1 c	18.4 a
1993	MR	Vf				16.3 b	20.0 a	21.5 a
	MM					6.7 c	14.6 b	22.2 a
1997	MR	Bv	21.2 c	23.2 b	24.0 a	15.5 d	20.4 b	23.1 a
	MM		18.5 c	21.8 b	23.4 a	11.6 e	17.8 c	22.9 a
2000	MR	Bv	17.3 c	20.5 a	20.0 a	10.2 d	17.9 b	20.4 a
	MM		16.5 d	19.1 b	19.8 b	8.7 e	15.2 c	20.4 a

Statistical significances[4]

Year	TA			PA		
	MM / MR	N rate	Inter-action	MM / MR	N rate	Inter-action
1988	NS			NS		
1991	**	***	***	***	***	***
1993				**	***	***
1997	NS	***	NS	*	***	***
2000	*	***	NS	**	***	*

[1] Bv = fodder beet; Vf = field bean.
[2] kg N ha^{-1} per year.
[3] Values within a TA x year or a PA x year combination with different letters are significantly different at $\alpha = 0.05$ (Newman-Keuls test).
[4] *** = $P < 0.001$; ** = $P < 0.01$; * = $P < 0.05$; NS = not significant.

indicated that the yields of maize in monoculture and of maize grown in rotation responded differently to fertilizer N. Indeed, except for the 2000 season, statistical analysis showed significantly ($P < 0.05$) higher yield responses for the maize in monoculture than for the maize grown in rotation.

On the *ley–arable crop plots*, in the second year after ploughing-in the three years old grass leys (1991, 1997 and 2000), silage maize clearly outyielded the maize on the permanently cropped plots. This was caused by the enhanced N-mineralization after ploughing-in the grass leys (Nevens & Reheul, 2001a). After such a relatively short grassland period, we recorded yield increases for silage maize grown after fodder beet (significant in 1991 and 2000, non-significant in 1997) compared with maize in the second year in monoculture. Again, at 180 kg N ha^{-1}, this positive effect decreased to non-significant differences. Compared with the permanently cropped plots, the relative size of this rotation effect was smaller: it varied from 5 to 21% at 0 kg N ha^{-1} and from –2 to 3% at 180 kg N ha^{-1}.

Economically optimum N fertilizer rate

The calculated levels of N_{opt}, at critical P values of 10 and 30, are summarized in Table 4. We did not allow N_{opt} to exceed 170 kg N ha^{-1} per year since this is the maximum amount of mineral N fertilization that is legally permitted on silage maize in Flanders (Anon., 2000). At P = 10, N_{opt} was higher on the permanently cropped plots (PA) than on the plots with a ley–arable crop rotation (TA), and more than once the calculated value exceeded the amount of 170 kg N ha^{-1}. Crop rotation significantly decreased the level of N_{opt} in 1993, 1997 and 2000, but the corresponding yields (according to the quadratic regression model) of MR and MM silage maize were comparable or even higher for the MR maize.

An increase of P from 10 to 30 markedly decreased the level of N_{opt} for the crop rotation plots. In 1991, 1993, 1997 and 2000 this decrease was 20, 50, 46 and 23 kg N ha^{-1}, respectively. For the maize in monoculture no decrease in N_{opt} was observed; N_{opt} remained 170 kg N ha^{-1}.

Also on the plots with a ley–arable crop rotation, N_{opt} for maize following fodder beet was lower than for second-year maize in monoculture: in 1991, 1997 and 2000, N_{opt} at P = 10 decreased with 38, 29 and 20 kg N ha^{-1}, respectively. On the same plots, an increase of P from 10 to 30 decreased the levels of N_{opt} most distinctively on the crop rotation subplots (MR): 88 kg N ha^{-1} in 1991, 95 kg N ha^{-1} in 1997 and 37 kg N ha^{-1} in 2000. On the MM subplots these decreases were 54, 64 and 69 kg N ha^{-1}, respectively.

Ear fraction of the silage maize crop

In 2000, the ear yields and the ear fractions of total DM yield were low, probably due to the very wet month of July (critical pollination period) when total rainfall was 157 mm, which is 121% more than the long-term average for the Melle.

In 1991 and 1993, the ear fraction of the total DM yield on the permanently cropped plots (PA) was significantly ($P < 0.01$) higher for the maize grown in crop

Table 4. Optimum N fertilizer rate (N_{opt}, kg N ha^{-1}), corresponding predicted silage maize yield (t DM ha^{-1}), and fertilizer N saving (kg N ha^{-1}) compared with the PA MM treatment. (MM = maize in monoculture, MR = maize in crop rotation; PA = permanently cropped plots, TA = second year after a three years old grass ley).

Year	Treatment	N_{opt}		N saving		DM yield at N_{opt}	
		MM	MR	MM	MR	MM	MR
P = 10[1]							
1991	PA	170[2]	170		0	17.9	18.7
	TA	153	115	17	55	18.9	18.5
1993	PA	170	137		33	21.7	21.4
1997	PA	170	164		6	22.6	23.0
	TA	146	117	24	53	23.3	23.8
2000	PA	170	143		17	19.2	20.6
	TA	119	99	51	71	19.8	20.9
P = 30							
1991	PA	170	150		20	17.9	18.1
	TA	99	27	71	143	17.8	16.7
1993	PA	170	87		83	21.7	20.4
1997	PA	170	118		52	22.6	22.1
	TA	82	22	88	148	22.0	21.9
2000	PA	170	120		55	19.1	20.1
	TA	50	62	125	113	18.4	20.2

[1] P = critical level of marginal yield response (kg DM per kg N).
[2] When the calculated N_{opt} was higher than 170 kg N ha^{-1}, a fixed value of 170 kg N ha^{-1} was used.

rotation than for the maize in monoculture. The values converged with increasing N fertilizer level. In 1997 and 2000, the difference was not statistically significant. On the ley–arable crop rotation plots (TA), the difference between the ear fractions of the MM and the MR treatments was never statistically significant.

Figure 4 shows that the ear fraction was clearly enhanced by an increase in N yield, at least on the PA plots. High N applications on silage maize did not jeopardize grain yields.

N yield and N content

Crop rotation increased the N yield of the silage maize (Table 5). On the permanently cropped plots (PA), without N fertilization N yield of the maize on the MR subplots compared with the maize on the MM subplots was 7–25 kg N ha^{-1} more when

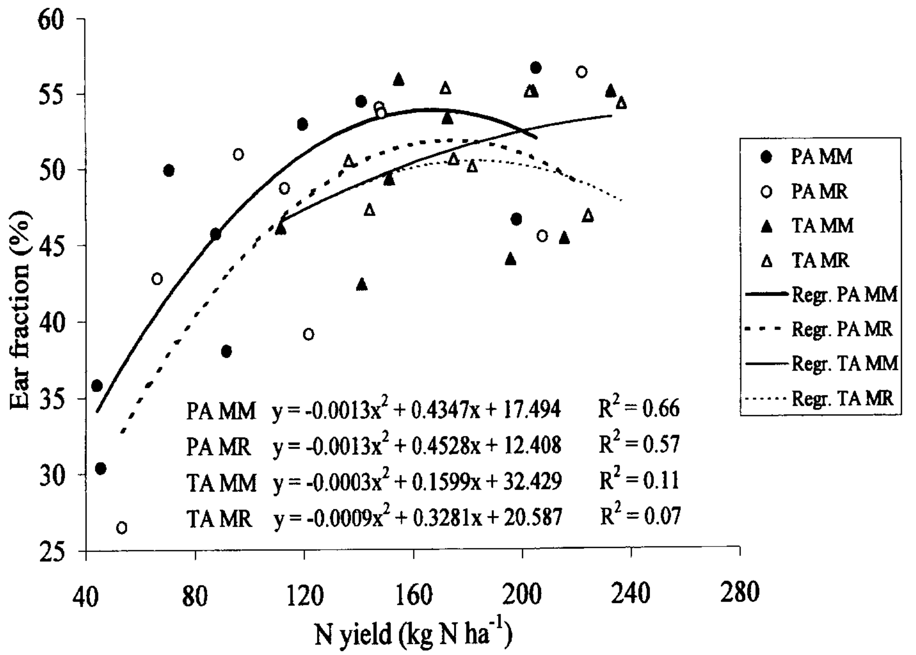

Figure 4. Ear fraction of silage maize grown in crop rotation (MR) or in monoculture (MM) on permanently cropped plots (PA) or in the second year after a three years old grass ley (TA), in relation to N yield.

following fodder beet, and 104 kg N ha^{-1} more when following field bean. At the highest N fertilizer rate (180 kg N ha^{-1}) the extra N taken up by the maize was 8–17 and 44 kg N ha^{-1} following fodder beet and field bean, respectively.

On the ley–arable crop rotation plots (TA), the N yield by the silage maize was markedly higher than on the permanently cropped plots (PA). As demonstrated by Nevens & Reheul (2001a), this was caused by the higher DM yields and higher N contents resulting from a large release of N following the ploughing-in of the grass ley. Within the TA treatments, maize following fodder beet also exported more N than maize following maize. Only in 1997, this difference was not statistically significant.

On the PA and TA plots the relative gain in N yield by the rotationally cropped maize (MR) compared with maize in monoculture (MM) was higher than the observed relative DM yield gains, indicating a higher N content of the MR maize. The measured N content of the rotational maize (MR) was indeed significantly higher than that of the MM maize on both PA and TA plots (Table 6).

The effect was very distinctive when maize followed field bean (1993). But also following fodder beet the N content of the maize was significantly higher than on the MM subplots. On the PA plots this was observed at all N fertilizer rates.

Table 5. N yield (kg N ha^{-1}) for silage maize grown in rotation (MR) or in monoculture (MM), in the second year after a three years old grass ley (TA) or on permanently cropped plots (PA), in relation to N fertilizer rate.

Year	Treat-ment	Previous crop[1]	TA			PA		
			N rate[2]			N rate[2]		
			0	75	180	0	75	180
1991	MR	Bv	136 c[3]	175 a	182 a	66 e	113 c	149 a
	MM		111 d	151 b	173 a	44 f	88 d	141 b
1993	MR	Vf				143 c	201 b	247 a
	MM					39 e	95 d	203 b
1997	MR	Bv	172 c	203 b	237 a	96 e	148 c	222 a
	MM		155 c	204 b	233 a	71 f	120 d	205 b
2000	MR	Bv	144 c	224 a	224 a	53 e	122 b	208 a
	MM		141 c	196 b	216 a	46 e	92 d	198 b
			Statistical significances[4]					
			TA			PA		
			MM / MR	N rate	Inter-action	MM / MR	N rate	Inter-action
1991			***	***	*	***	***	**
1993						***	***	***
1997			NS	***	NS	**	***	*
2000			**	***	*	*	***	*

[1] Bv = fodder beet; Vf = field bean.
[2] kg N ha^{-1} per year.
[3] Values within a TA x year or a PA x year combination with a different letter are significantly different at $\alpha = 0.05$ (Newman-Keuls test).
[4] *** = $P < 0.001$; ** = $P < 0.01$; * = $P < 0.05$; NS = not significant.

N fertilizer replacement value (NFRV) of preceding field bean or fodder beet

Using the quadratic yield response curves of the MM and MR silage maize in 1993, a NFRV of 94 kg N ha^{-1} was calculated for the 1992 field bean (Figure 5). When the N yield quadratic curves were used, the NFRV was 126 kg N ha^{-1}.

NFRVs calculated in a similar way for fodder beet preceding silage maize are given in Table 7. If we assume that the NFRV provides a reasonable estimate for potential N savings, it can be concluded that for silage maize following fodder beet on permanently cropped land, on average 31 kg less fertilizer N was needed than for maize in monoculture. Following three years of grass ley and a subsequent maize crop or a fodder beet crop these savings were 89 and 125 kg N ha^{-1}, respectively.

Table 6. N content (g per kg DM) of silage maize grown in rotation (MR) or in monoculture (MM), in the second year after a three years old grass ley (TA) or on permanently cropped plots (PA), in relation to N fertilizer rate.

Year	Treatment	Previous crop[1]	TA N rate[2] 0	TA 75	TA 180	PA N rate[2] 0	PA 75	PA 180
1991	MR	Bv	8.6 d[3]	9.8 a	9.8 a	7.1 e	7.6 c	7.9 a
	MM		8.5 d	8.9 c	9.1 b	6.7 f	7.2 d	7.7 b
1993	MR	Vf				8.8 d	10.0 b	11.5 a
	MM					5.8 f	6.5 e	9.1 c
1997	MR	Bv	8.1 e	8.8 c	9.9 a	6.2 e	7.2 c	9.6 a
	MM		8.4 d	9.4 b	9.9 a	6.1 e	6.7 d	9.0 b
2000	MR	Bv	8.3 c	10.9 a	11.2 a	5.2 e	6.8 c	10.2 a
	MM		8.5 c	10.3 b	10.9 a	5.2 e	6.0 d	9.7 b

Statistical significances[4]

Year	TA MM / MR	TA N rate	TA Interaction	PA MM / MR	PA N rate	PA Interaction
1991	***	***	***	***	***	NS
1993				***	***	***
1997	***	***	***	**	***	***
2000	NS	***	***	*	***	***

[1] Bv = fodder beet; Vf = field bean.
[2] kg N ha^{-1} per year.
[3] Values within a TA x year or a PA x year combination with a different letter are significantly different at $\alpha = 0.05$ (Newman-Keuls test).
[4] *** = $P < 0.001$; ** = $P < 0.01$; * = $P < 0.05$; NS = not significant.

Cumulative DM yields over the period 1990–2000

Figure 6 presents the cumulative DM yields over the period 1990–2000 for the forage crops from the MR subplots and for the maize from the MM subplots, on the PA as well as on the TA plots (LA1 and LA2 combined). At the highest N fertilizer rate (180 kg N ha^{-1} per year; field bean 25 kg ha^{-1} per year), the obtained yields are almost equal, indicating that the different rotation systems had the same DM yield potential. On the PA plots, the crop rotation including silage maize (5/11), fodder beet (4/11) and field bean (2/11) yielded 48% more DM than silage maize in monoculture without N fertilization. On the TA plots – with silage maize (6/11), fodder beet (3/11) and field bean (2/11) – this advantage was 11%. The overall yield level of the ley–arable crop rotation plots, however, was 61% higher than that of permanently cropped plots, owing to the earlier mentioned large N mineralization following the ploughing-in of the grass ley.

When 75 kg of mineral N ha^{-1} per year was applied (except for the field bean), the

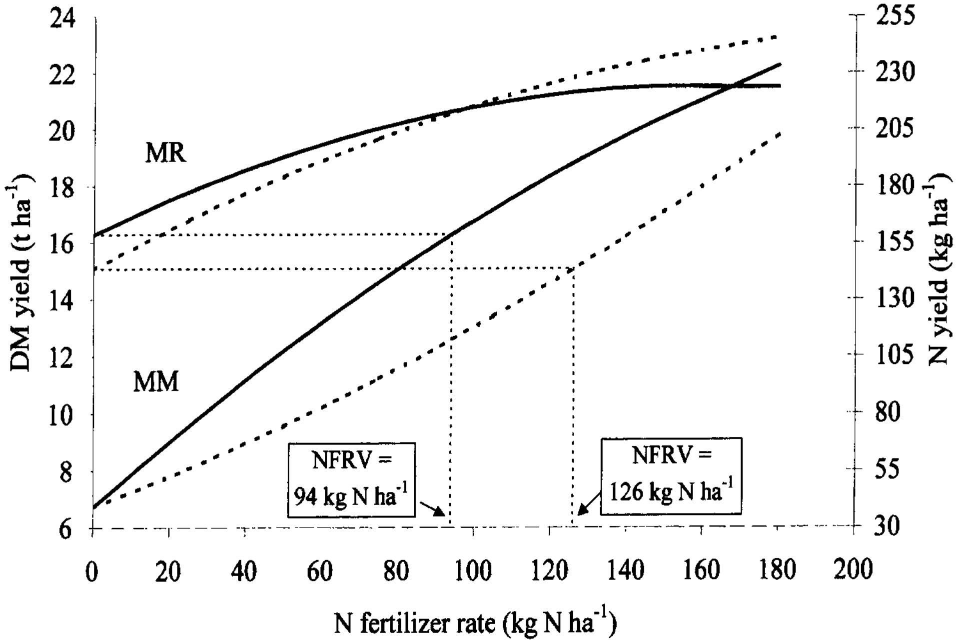

Figure 5. DM yields (———) and N yields (- - - -) of silage maize in monoculture (MM) and silage maize grown in rotation following field bean (MR), in relation to N fertilizer rate. An illustration of the method to determine the N fertilizer replacement value (NFRV) of the field bean.

Table 7. N fertilizer replacement values (NFRV; kg N ha^{-1}) of preceding crops for the subsequently grown silage maize.

Year	Preceding crops		
	Field bean followed by fodder beet	3 yrs of grass followed by maize	3 yrs of grass followed by fodder beet
Based on DM yield curves			
1991	36	89	133
1997	44	84	133
2000	14	95	108
Average	31	89	125
Based on N yield curves			
1991	17	60	100
1997	41	121	142
2000	16	130	133
Average	25	104	125

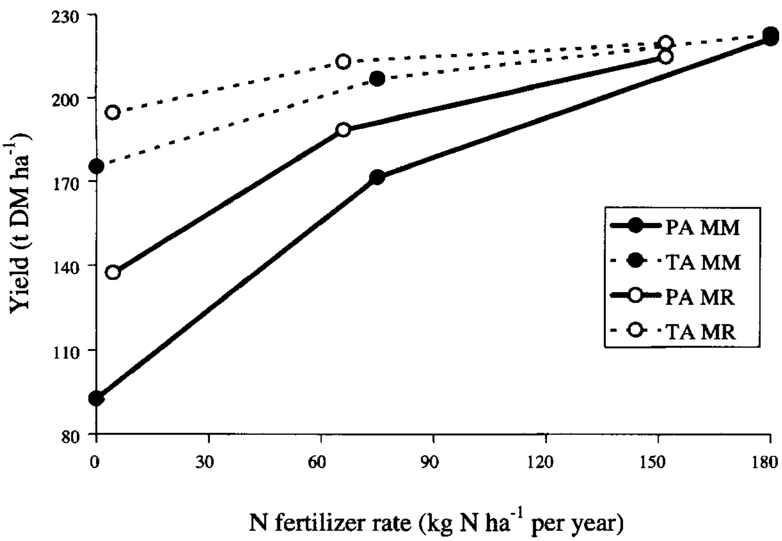

Figure 6. DM yields of the forage crop rotations (MR) and of the maize in monoculture (MM) in relation to N fertilizer rate. PA: cumulative yields on permanently cropped plots (1990–2000). TA: cumulative forage crop DM yields on the three years crop rotation plots (1990–1992 + 1993–1995 + 1996–1998 + 1999–2000).

benefits of the crop rotation (MR versus MM) on permanently cropped land (PA) and on ley–arable crop rotation land (LA) were 10 and 3%, respectively. In that situation the overall yield increase of the LA plots compared with the PA plots was 17%. With 180 kg N ha^{-1}, the total yield differences were reduced to a minimum or were even slightly negative.

Silage maize ear yield progress in the period 1990–2000

The ear DM yields on the PA MM subplots over the period 1990–2000 at the highest N fertilizer rate (180 kg N ha^{-1}), showed a clear steady increase (except for 2000; Figure 7). At 75 kg N ha^{-1}, the increase was less, and at 0 kg N ha^{-1} there was almost no increase. With crop rotation (PA MR), maize yield increases were also observed at the lower N rates (0 and 75 kg N ha^{-1}). Again, the 2000 growing season – with unfavourable weather conditions for pollination – was a marked exception.

Discussion

Our results confirm the beneficial effect of crop rotation on the yield of silage maize. Both, the non-leguminous fodder beet and the leguminous field bean were effective rotation crops preceding maize. Even during the relatively short cropping periods of a three-year ley – three years arable crop rotation, growing maize after fodder beet resulted in significant yield increases compared with silage maize upon

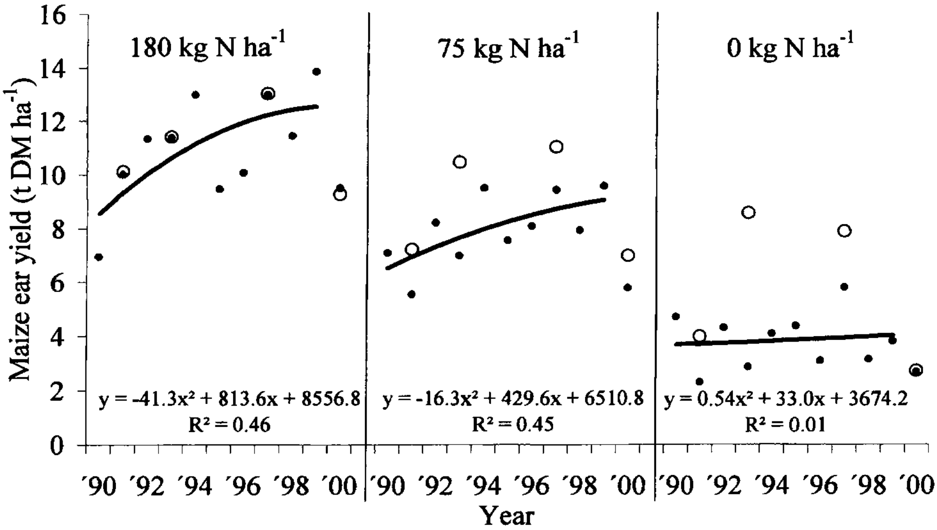

Figure 7. Silage maize ear DM yields of the permanently cropped plots in relation to N fertilizer rate. Maize grown in monoculture or in rotation (1990–2000). ● = maize in monoculture; ○ = maize in rotation; ——— = regression for maize in monoculture.

silage maize. The relative yield gains were highest without N fertilization. The positive rotation effect disappeared almost entirely at a N rate of 180 kg N ha^{-1}, which is in agreement with results from literature on 'N-contribution effects'. This effect seems quite logical in the case of the leguminous field bean, which is known to have a high Nitrogen Fertilizer Replacement Value (Hestermann, 1988 in Paré *et al.*, 1993). We found NFRVs of 94 kg N ha^{-1} (based on DM yield curves) and 126 kg N ha^{-1} (based on N yield curves), which is in agreement with values of 60–125 kg N ha^{-1} reported by Wright (1990) and Paré *et al.* (1993). The yield gains for maize following field bean exceeded those of maize following fodder beet. Nevertheless, even this root crop had a significant positive effect on maize at the low N fertilizer rates. The average NFRV for fodder beet of 31 kg N ha^{-1} was below the one for field bean, as was expected for this non-leguminous crop of which the leaves were always removed from the field at harvest. In Nevens & Reheul (2001a) we already emphasized the importance of fodder beet as a first crop following the grass in the ley–arable crop rotation: the beet crop uses the released grassland-N in a far more efficient way than the silage maize.

The decreasing positive effect of crop rotation with increasing N fertilizer level indicated that raising the N fertilizer rate could easily offset the negative effects of maize in monoculture. In other words, to reach maximum economical profits, lower levels of fertilizer N had to be applied in rotationally grown silage maize.

To determine N_{opt}, a quadratic yield response model was used. We are aware of the fact that a quadratic model, compared with quadratic-plus-plateau response models, could lead to an overestimation of N_{opt} (Cerrato & Blackmer, 1990; Bullock & Bullock, 1994). But the three N fertilizer rates used did not allow us to describe the yield by a quadratic-plus-plateau model as suggested by these authors. However, the following considerations supported our confidence in the use of quadratic yield response curves. Cerrato & Blackmer (1990) and Bullock & Bullock (1994) considered a much wider range of N rates (up to 360 kg N ha^{-1}) and obtained a response curve that levelled off at about 175 kg N ha^{-1}. We considered a maximum N rate of 180 kg N ha^{-1}, but we did not go beyond a maximum N_{opt} of 170 kg N ha^{-1} since this is the legal maximum in Flanders for mineral N fertilizer on silage maize. Furthermore, Cerrato & Blackmer (1990) admitted that overestimations of N_{opt} were most obvious when cost:value ratios lower than 10 were considered. At such ratios, N_{opt} shifts towards the flatter part of the response curve, where small differences in slope correspond with relatively large differences in rates of N fertilizer. We worked at cost:value ratios up to 30. At such high ratios only the steep, left part of the response curve is considered. NFRVs were also determined in this range. And in fact we observed a good agreement between the average possible N savings calculated by subtracting N_{opt} (at P = 30) and the N savings estimated by using NFRVs derived from yield response curves. With the N_{opt} difference method for P = 30, we found average N savings of 42, 95 and 135 kg N ha^{-1} for the PA MR, TA MM and TA MR treatments, respectively, compared with PA MM (Table 4, silage maize following fodder beet in the MR treatment). The corresponding NFRVs were 31, 89 and 125 kg N ha^{-1} (Table 7).

The yields obtained at N_{opt} for MR maize (calculated according to the quadratic model) were comparable with those for MM maize (at the higher N_{opt} levels).

Silage maize in a crop rotation is less responsive to N fertilization. This means that in case the use of N fertilizer would be drastically restricted (even more than today), smaller DM yield decreases will be observed for maize in crop rotation than for maize in monoculture. Furthermore, should fertilizer N prices rise – resulting in a higher P value – the N_{opt} for MR maize could be decreased substantially compared with MM maize. Nevertheless, the yield levels of MM and MR would remain comparable (Table 4).

The year 1991 was not favourable for maize growing, owing to the bleak months of May and June (Figures 2 and 3). The average maize yield in 1991 was about 25% less than in 1997, but the absolute effect of crop rotation (MR versus MM) in these two years was about the same (Table 3). So the relative effect of crop rotation was higher in the 'stress year' 1991. This indicates that crop rotation could also be a useful tool to buffer crop production against climatic vagaries. However, when during the 2000 season an extremely wet July resulted in bad pollination and hence in bad ear formation, crop rotation had only a small, non-significant effect.

During growing seasons with favourable conditions for pollination and ear formation, not only yield was positively affected. We observed that rotational cropping could increase the ear fraction of the total DM yield. This increase results in an increased energetic feed value of the ensiled product since higher ear fractions mean a higher net energy content (Gross, 1986; Gross & Peschke, 1980) and a higher starch content (Van Waes *et al.*, 1997). So not only quantity, also quality is improved when maize is grown in rotation.

The indication that yield reductions in monoculture can be offset by increasing the N fertilizer rate – even to supra-optimal levels – is confirmed when we study the progress of silage maize ear DM yields during the period 1990–2000. With monoculture, the progress in maize breeding was observed only if high amounts of fertilizer N were applied. In rotationally cropped silage maize, less N input was needed to observe this progress.

In arable farming systems that are faced with (future) restrictions on N fertilizer use, it could be advantageous to abandon monoculture and replace it by crop rotation whenever possible, so enabling to maintain crop production and to exploit the benefits of plant breeding more efficiently.

Conclusions

Compared with maize in monoculture, maize grown in rotation resulted in higher DM yields and higher N yields, even during three-year cropping periods alternated with three-year ley periods. When maize was grown in rotation, less N fertilizer had to be applied to obtain economically optimum yields. In case N fertilizer prices would increase or N fertilization would be severely restricted, a rotational cropping system offered more possibilities to decrease N fertilizer use without severe yield losses than monoculture. The progress in maize breeding was better expressed and was exploited in a more efficient way when silage maize was grown in rotation than when grown in monoculture, especially if considered in the general context of decreased N inputs.

We therefore agree with – and underline – the statements that multifunctional crop rotation is a strategy to prevent high nutrient losses (Rovers & Kroonen, 1999) and that it is a major instrument in the concept of sustainable or organic farming (Köpke, 1998; Lampkin, 1990).

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