TOWARDS IMPROVED NITROGEN MANAGEMENT IN SILAGE MAIZE PRODUCTION ON SANDY SOILS

Promotoren:

dr.ir. P.C. Struik, hoogleraar gewas- en graslandkunde
dr.ir. O. Oenema, bijzonder hoogleraar nutriëntenstromen en bemesting

Co-promotor:

dr.ir. J.J. Neeteson, Themaleider Multifunctioneel en Duurzaam Landgebruik AB-DLO

Jaap Schröder

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ABSTRACT

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The maize cropping technique current in The Netherlands is associated with a low recovery of soil nitrogen in the crop and with considerable losses of nitrate to the groundwater. This thesis aims to identify factors that determine the partitioning of the nitrogen inputs from manure or artificial fertiliser over crop and losses to the environment, to identify techniques for improving the efficiency of nitrogen use by maize and to integrate them into an environmentally sound management system.
The effects of rates, time and methods of nitrogen application on the uptake of nitrogen by the crop and the loss of nitrogen to the groundwater, were studied in field experiments. When applied at economically suboptimal rates, nitrogen was recovered better by maize than when applied at the economically optimal rate. The yield loss associated with sub-optimal nitrogen rates could be limited by placing the nitrogen close to the maize roots. Cover crops reduced the yield loss in subsequent maize crops by recycling nitrogen that would otherwise leach out during winter. It is concluded that it is technically feasible to grow maize without unacceptable nitrate concentrations in the groundwater by a combination of measures including reduced nitrogen inputs, nitrogen placement and growing cover crops.

Additional keywords: apparent recovery, cover crop, fertiliser placement, fertiliser splitting, leaching, manure, mineralisation, minirhizotron, nitrate leaching, nitrification inhibitor, nitrogen recovery, phosphorus, placement, recovery, residual effect, residual nitrogen, response model, root distribution, root length density, silage maize, simulation, slurry, soil sampling, *Zea mays* L.

Reference to the contents of Chapters 2 to 8 should be made by citing the original publications.

WOORD VOORAF

Een proefschrift staat gewoonlijk op naam van één persoon maar zou er nooit kunnen zijn zonder de betrokkenheid, op vele manieren, van talloze personen. Een aantal van hen wil ik met name noemen.

Allereerst bedank ik mijn promotoren professor dr ir P.C. Struik en professor dr ir O. Oenema, en mijn co-promotor dr ir J.J. Neeteson. Paul, Oene en Jacques, toen ik op aandrang van anderen maar eens werk maakte van een serieuze schets van de inhoud van een proefschrift, reageerden jullie met een vanzelfsprekendheid die, zonder dat jullie het misschien merkten, de ergste twijfel over mijn vermogen tot slagen deed wegnemen. In de periode daarna volgden de manuscripten elkaar in wisselend tempo op met minachting voor het aanvankelijke tijdschema. Jullie voorzagen de manuscripten van kritische noten, confronteerden cijfers en tekst met elkaar en voelden mij flink aan de tand. Kortom, jullie kennis en kunde zijn een grote steun geweest.

Van mijn directeur, dr ir J.H.J Spiertz, weet ik nog steeds niet of zijn aansporingen om te promoveren stoelden op zorg om mij, om die van het instituut of om die van beide. Hoe dan ook, Huub, achteraf ben ik toch wel blij dat je nooit bent opgehouden met aandringen, hoe vaak ik je ook te slim af probeerde te wezen met een eigenaardig mengsel van cynisme over academische eigendunk, verwijzing naar nieuwe taken, ontelbare hobby's en andere smoesjes. Je had gelijk, een proefschrift blijft een mooi voertuig om tot een nette afronding te komen. Bedankt voor de gelegenheid die het DLO Instituut voor Agrobiologisch en Bodemvruchtbaarheidsonderzoek (AB-DLO) mij geboden heeft het werk af te maken.

De meeste hoofdstukken van dit proefschrift zijn gebaseerd op onderzoek dat door mij met anderen is uitgevoerd. In mijn dank wil ik dan ook vooral mijn co-auteurs betrekken: Ko Groenwold, Tania Zaharieva (Poushkarov Institute, Sofia), Gerard Brouwer, Lammert ten Holte, Herman van Keulen, Joop Steenvoorden (SC-DLO), Wim van Dijk (PAV), Willy de Groot (SC-DLO), Gert-Jan Noij (SC-DLO), Jacques Withagen en Jacques Neeteson. Daarnaast wil ik de vakgenoten bedanken die, al dan niet anoniem, manuscripten becommentarieerden. Ook ben ik de medewerkers van de proefboerderijen Heino, Cranendonck, Droevendaal, De Marke en van de proeftechnische diensten en laboratoria van het Proefstation voor de Akkerbouw en de

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Stellingen

1. Bij opvolging van het huidige stikstofbemestingsadvies neemt snijmaïs ongeveer de helft van de toegediende minerale stikstof op.

Dit proefschrift

2. Bij de teelt van maïs is het relevanter om de hoeveelheid minerale bodemstikstof in het najaar dan in het voorjaar te bepalen.

Dit proefschrift

3. Toediening van mest in alleen dat deel van de bodem waarin maïs intensief wortelt, rechtvaardigt lagere mestgiften en beperkt de verliezen van stikstof.

Dit proefschrift

4. Vanggewassen beperken de uitspoeling van stikstof alleen als minder stikstof gegeven wordt dan geadviseerd in het gangbare stikstofbemestings-advies; de in die zin onvoorwaardelijke subsidies op de teelt van een vanggewas in de Gelderse Vallei, zijn daarom slecht besteed geld.

Dit proefschrift; Info Stichting Vernieuwing Gelderse Vallei

5. Alleen met aanvullend beleid zullen de van overheidswege voorgestelde stikstofverliesnormen, op droge zandgronden met veel maïs in het bouwplan, leiden tot acceptabele nitraatgehalten in het bovenste grondwater.

Dit proefschrift

6. In veldonderzoek zijn het tijdstip en de plaats van bemesting dikwijls verstrengeld en dit maakt de conclusies van bijvoorbeeld Timmons & Baker aangaande de voordelen van mestplaatsing aanvechtbaar.

Timmons & Baker, 1992. Agronomy Journal 84: 490-496

7. Paarse maïsplanten zijn geen sluitend bewijs voor fosfaatgebrek.

Knoll et al., 1964. Soil Science Society Proceedings: 400-403

8. De in Nederland ontwikkelde geïntegreerde bedrijfssystemen voor de akkerbouw gaan gepaard met stikstofoverschotten en stikstofresiduen in de bodem die volgens, respectievelijk, de Stikstof Deskstudie en de Commissie Stikstof milieukundig ontoelaatbaar zijn.

Schröder et al., 1996. European Journal of Agronomy 5: 181-191

9. 'Onvermijdbaar stikstofverlies' is vermijdbaar.

Schröder & Vos, 1995. AB-DLO Thema's 3: 37-63

10. Huidige LNV-onderzoeksprogramma's duren te kort om een betrouwbare uitspraak te kunnen doen over (het uitblijven van) opbrengstdaling bij voortgezette toepassing van evenwichtsbemesting.

11. De scheiding van functies in de Groene Ruimte met Nieuwe Natuur als lokkertje, is bedreigender voor de das (*Meles meles* L.) dan de verweving van functies in het kader van Agrarisch Natuurbeheer.

12. Ook op biologische melkveehouderijbedrijven is snijmaïs een goede keuze.

13. Met mest is het als met Martini: '*the right place and the right time*' zijn belangrijk, maar het komt natuurlijk vooral aan op de juiste hoeveelheid.

Stellingen behorende bij het proefschrift '*Towards improved nitrogen management in silage maize production on sandy soils*' van Jaap Schröder, Wageningen, 8 april 1998.

Groenteteelt in de Vollegrond (PAGV) en AB-DLO erkentelijk. Zij zorgden voor een goed verloop van de vele proeven. Jimmy Robot tekende een fraaie dwarsdoorsnede van het Wageningen Rhizolab en plaatsgenoot Roel Pannekoek fotografeerde maïs in een natuurlijke omgeving voor een toepasselijke voorplaat. Joy Burrough-Boenisch verbeterde het door mij in het eerste en de laatste twee hoofdstukken gebruikte Engels. De nette opmaak van het proefschrift, tenslotte, is te danken aan Rina Kleinjan-Meijering. Zonder jullie allen was het nooit zo gelukt.

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De echte basis voor een proefschrift ligt natuurlijk niet bij collega's maar bij het nest waaruit je komt. Willem en Christien Schröder, jullie gaven je kinderen volop de kans waarbij ik me niet kan herinneren daar tot vervelens toe op gewezen te zijn. Jullie weten niet half hoe plezierig dat was. Met jullie brede belangstelling maar allesbehalve landbouwkundige achtergrond, hoorden jullie me uit en weten inmiddels meer van maïs dan een doorsnee 'Wageninger'. Wie weet was het allemaal heel anders gelopen als ik indertijd niet dat hoekje in de achtertuin naar mijn eigen inzicht had mogen ontginnen. Als er weer gespit moet worden, roepen jullie maar.

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Jaap Schröder

CONTENTS

CHAPTER 1

GENERAL INTRODUCTION

1.1 Present status of silage maize in The Netherlands

Maize is a relatively new crop in The Netherlands, as it is in all countries in Northwest Europe. The area under maize rose from a few thousand hectares in 1970 to almost 250 000 hectares in 1995, most of which are found on sandy soils in the eastern and southern parts of the country. Between 1970 and 1995 maize replaced more than 25 percent of the grassland in these regions (Figure 1.1).

The maize is predominantly used as whole crop silage for dairy cows. Dairy farmers have come to appreciate maize as a roughage with a relatively stable yield and quality. Mature silage maize has a low nitrogen (N) content usually ranging from 0.010 to 0.014 kg N kg^{-1} dry matter (DM) (Figure 1.2). The crop provides an excellent supplement to protein-rich grass, the major component of dairy cow rations (Van Vuuren *et al.*, 1993). Maize is easy to

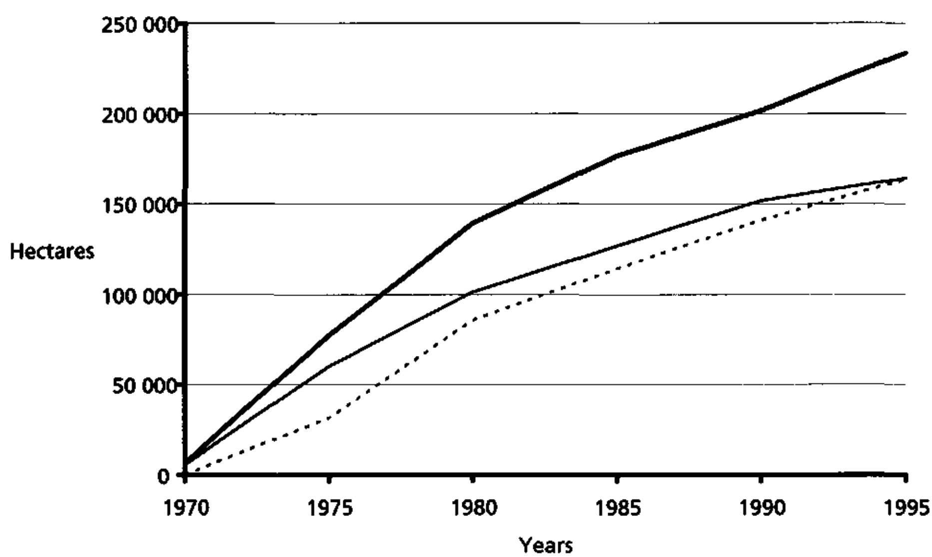

Figure 1.1. Hectarage of silage maize grown in The Netherlands as a whole (—) and in the southern and easterns provinces (——), and the cumulative decrease in the grassland hectarage in these provinces, from 1970 to 1995 (-----).

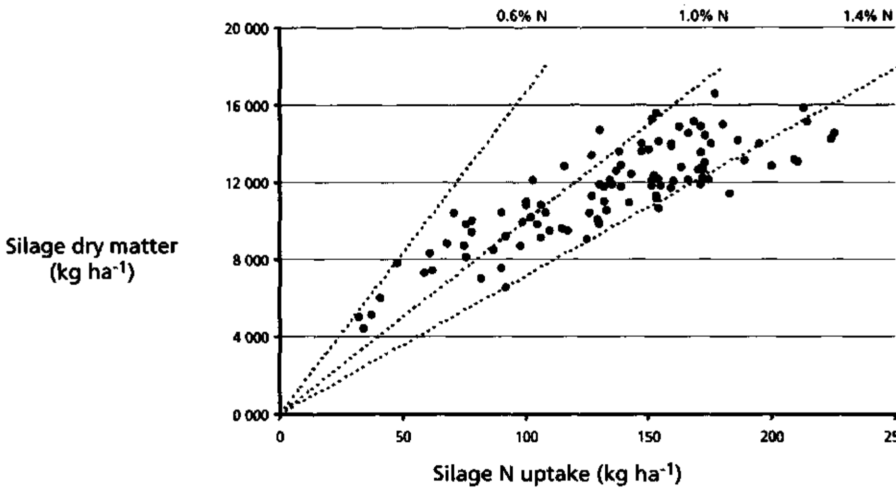

Figure 1.2. Relationship between the N uptake and DM yield of silage maize at maturity (combined data of Meisinger *et al.*, 1985; Schröder, 1985b; 1985c; Jokela & Randall, 1989; Timmons & Baker, 1991; Salardini *et al.*, 1992; Jokela, 1992a).

grow, many practices can be contracted out, and it is fairly tolerant of continuous cropping (Van Dijk *et al.*, 1996). The crop can tolerate heavy manure applications (Schröder & Dilz, 1987) and, consequently, maize land has been frequently used for manure disposal. This has undoubtedly contributed to the popularity of maize on intensively managed dairy farms and explains why whole crop silage maize is the only crop grown on many intensive pig farms. Maize grown by these pig farmers is sold to neighbouring dairy farmers.

Maize is a thermophilic plant with an optimal growth temperature in the range of 25-30°C (Grobbelaar, 1963; Walker, 1969; Miedema, 1982). The Netherlands is on the northern border of the European zone where maize can be grown successfully, as indicated by the average daily temperatures, which range from 12 to 16°C during the growing season (Figure 1.3). Hence, the yield potential of maize is greatly constrained by the available heat sum. On sandy soils, particularly, there is a high risk that yields will also be limited by drought. Average monthly rainfall during the growing season ranges from 50 to 90 mm in The Netherlands (Figure 1.4). Consequently, silage maize yields on an individual site may vary from 10 ton DM ha^{-1} yr^{-1} in dry years to 16 ton DM ha^{-1} yr^{-1} in years with sufficient rainfall.

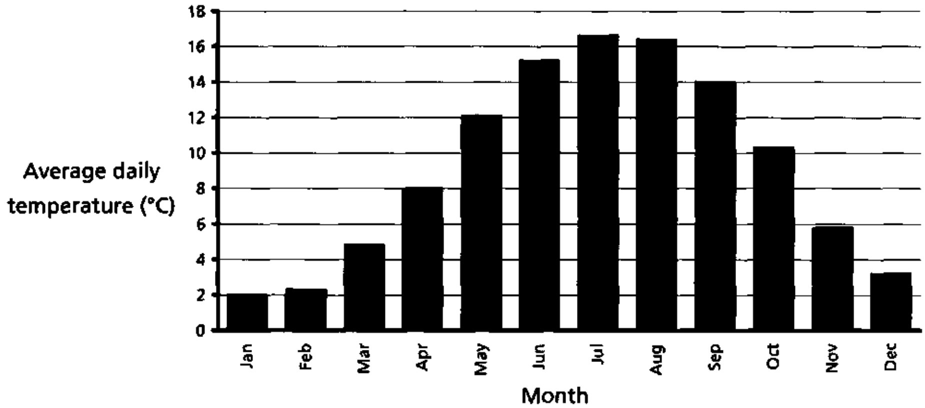

Figure 1.3. Long-term average daily temperature (°C) in De Bilt, The Netherlands (1951-1980).

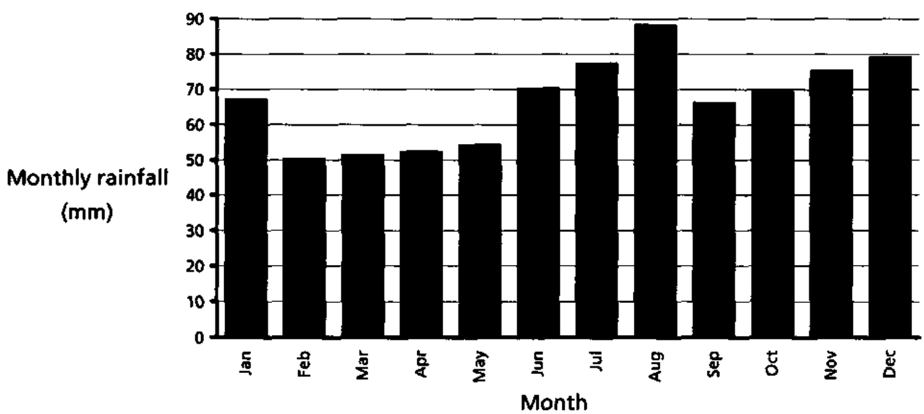

Figure 1.4. Long-term average monthly rainfall (mm) in De Bilt, The Netherlands (1951-1980).

Currently, maize cropping in The Netherlands is associated with considerable losses of nutrients to the environment. Maize land on sandy soils is amply manured from February onwards; this can be sensed by the eye, if not by the nose. The ammonia emission resulting from this manuring is associated with damage to the surrounding vegetation, eutrophication of nearby nature conservation areas and soil and water acidification (Van Der Eerden *et al.*, 1997). The amount of nutrients applied usually exceeds the amount exported via crop produce. The crop is harvested in autumn and the land is usually left bare from October until the end of April. This questionable cycle is repeated year after year on the same field. It often results in nitrate concentrations in groundwater that exceed the EC standard for drinking water (Anonymous, 1980). Average nitrate concentrations under maize land in the Netherlands exceed the nitrate concentrations found under other arable land and grassland (Van Duijvenbooden, 1989; Van Swinderen *et al.*, 1996).

One could argue that emissions of N from maize land are predominantly caused by the excessive use of manure and that legislation rather than research is therefore needed to change the situation. Legislation on the rate, method and timing of manure applications was introduced in The Netherlands in 1987 (Goossensen & Meeuwissen, 1990; Anonymous, 1995). However, it did not result in an immediate decrease in nitrate leaching under maize land. There are three reasons for this. Firstly, the rates initially permitted were deliberately set high, to increase the farmers' acceptance of the legislation. Although the permitted rates for manuring maize land have gradually decreased over time (Goossensen & Meeuwissen, 1990), they still exceed crop demand. The second reason is that for a long time the legislation pertained to inputs via manure only. Inputs via artificial fertiliser will be addressed by legislation, shortly (Oenema *et al.*, 1997). Finally, the third reason why the implementation of legislation has not immediately resulted in an improvement of groundwater quality is the residual effect of manure. It may take many years for the organically bound N fraction in manure to decompose (Whitmore & Schröder, 1996). Consequently, a change in practice will not instantaneously be reflected in a change of emissions.

There are strong indications that emissions from maize land do not merely result from excessive manuring. The N emissions associated with maize cropping can be large, even at moderate input rates, as indicated by the considerable amounts of residual soil mineral N in October observed in Dutch experiments dating from the late seventies and early eighties (Table 1.1). The moisture retention capacity of sandy soils is too small to store the winter precipitation surplus of circa 300 mm, which means that the data presented on soil mineral N residues can be considered indicative of potential leaching losses during the subsequent winter (Prins *et al.*, 1988; Neeteson, 1994; 1995). Similar observations on soil mineral N residues after maize have been made in other countries (Russelle *et al.*, 1981; Jokela & Randall, 1989; Jokela, 1992a; Lorenz, 1992; Aufhammer *et al.*, 1996).

Table 1.1. Residual soil mineral N (0-60 cm depth, kg ha^{-1}) in October after silage maize grown on sandy soils without N or with moderate N inputs (Schröder, 1985b, 1985c)

Site	Mineral N input (kg ha^{-1})		Year						
	Fertiliser	Slurry	1976	1977	1978	1979	1980	1981	1982
Heino	0	0	153	45	26	-	33	26	34
	150	0	208	76	85	-	56	40	94
	0	130	-	-	-	-	137	45	70
Maarheeze	0	130	-	-	-	-	77	64	118

1.2 Crop, soil and husbandry characteristics

The long-term daily average temperature in The Netherlands in May is only 12°C. Consequently, N uptake of maize per unit of area is low during the first few weeks after emergence. When maize crops are exposed to a combination of low temperatures and a high light intensity, photosynthesis can be reduced by photo-inhibition for a long period (Schapendonk *et al.*, 1994). The yellow whorls resulting from low temperatures are a very common phenomenon in spring and yellowing is often misinterpreted as N deficiency. Farmers may wrongly react to such yellowing crops by giving supplementary N dressings.

Initially, biomass production is low because row widths of 0.7-0.8 m hamper full interception of light during the juvenile stages of the crop. The N uptake rate per ha is also low for that reason. At the end of May - beginning of June (i.e. circa three weeks after emergence), not more than 10 kg N ha^{-1} is usually taken up by the crop; this has risen to about 60 kg N ha^{-1} by the beginning of July. By mid August N uptake is almost completed; at this point, approximately 150-200 kg N ha^{-1} have been taken up (Figure 1.5). Daily average uptake rates in May, June, July and August are respectively 0.5, 1.5, 2.2 and 1.3 kg N ha^{-1}. On days with favourable weather conditions, however, uptake rates in densely planted maize crops may be as high as 10-15 kg N ha^{-1} (Karlen *et al.*, 1988).

Little N is taken up from mid August onwards and, as N mineralisation from soil organic matter continues, this may contribute to the accumulation of residual soil mineral N. Maize crops are usually not harvested before the end of September. This makes it relatively difficult to fully intercept the residual soil mineral N with cover crops.

Initially, the root system of a young maize crop incompletely exploits the nutrient and water reserves of the soil (Kiesselbach, 1949; Foth, 1962; Mengel & Barber, 1974; De Willigen & Van Noordwijk, 1987; Barber & Kovar, 1991). At low soil temperatures, roots do not penetrate deeply (Chaudhary & Prihar, 1974; Kuchenbuch & Barber, 1988; Tardieu & Pellerin, 1991). Low temperatures also result in a shorter specific root length (Kiel & Stamp, 1992); this implies that less root length is produced per unit of DM invested in the root system. Such root characteristics, combined with limited uptake rates of N and a small evaporative demand, may increase the probability of early losses of soil mineral N (Blackmer *et al.*, 1989; Evanylo, 1991; Magdoff, 1991; Binford *et al.*, 1992a; Killorn & Zourakis, 1992; Torbert *et al.*, 1993).

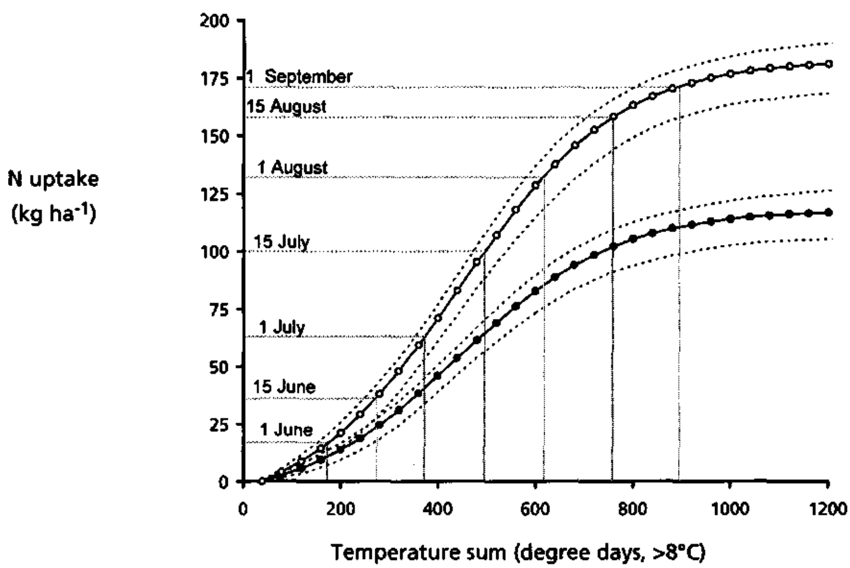

Figure 1.5. Nitrogen uptake (solid line indicating the average, dashed lines indicating the 80% probability interval) of N deficient (●) and non-deficient (O) silage maize, as related to the thermal time after planting (= April 20) (combined data from Schröder, 1990a; Schröder & Ten Holte, 1993; 1996; Schröder *et al.*, 1994; 1995).

The sandy soils in The Netherlands on which maize is mainly grown are more at risk of leaching than heavier soils. Their limited water retention capacity may decrease the moisture availability for the crop during summer. As well as having direct negative effects on transpiration and production, moisture stress can have an indirect negative effect by impeding the rate of nutrient transport in the soil matrix (De Willigen & Van Noordwijk, 1995). Both excess water and water deficits have been proposed as explanations for depressed yield and N uptake and for a decrease in the recovery of N (Lang, 1978; Legg *et al.*, 1979; Torbert *et al.*, 1992, 1993; Menelik *et al.*, 1994).
Crop husbandry techniques, too, may limit the utilisation of nutrients. Most maize land is fertilised with manure rather than with artificial fertilisers because in The Netherlands manure is plentiful in the regions where maize is grown. It is much more complicated to manage manure than to manage artificial fertilisers (e.g. Schröder *et al.*, 1996c). Moreover, frequent manure applications increase the N supplying capacity of a soil, and neither farmers nor researchers know exactly how to take this into account.

1.3 Recovery of nitrogen and the role of nitrogen in crop production

Nitrogen is an indispensable element for the optimal functioning of crops, so reducing the N input may depress the yield of maize. The availability of N affects the rate of leaf initiation, final leaf expansion and the foliar senescence rate. When N limits production, a positive relationship can be found between the amount of N taken up by a maize crop and the total leaf area (Figure 1.6). Under those circumstances, lack of N may reduce the leaf area throughout the growing season (Figure 1.7). The amount of leaf area has a direct positive effect on light interception and, consequently, on yield (Muchow, 1988; Sinclair, 1990; Van Keulen & Stol, 1991; Booij *et al.*, 1996). A rapid canopy closure may also reduce soil evaporation (Van Keulen & Stol, 1990) and suppress weeds. N may thus have additional, indirect positive effects on yields.
The conversion of intercepted light into biomass, expressed as the radiation use efficiency (RUE), also depends on N via effects on the foliar N content. Increases in RUE are reported up to an N content of 2 g m^{-2} leaf area (Muchow & Davis, 1988; Sinclair, 1990). Apart from having a direct

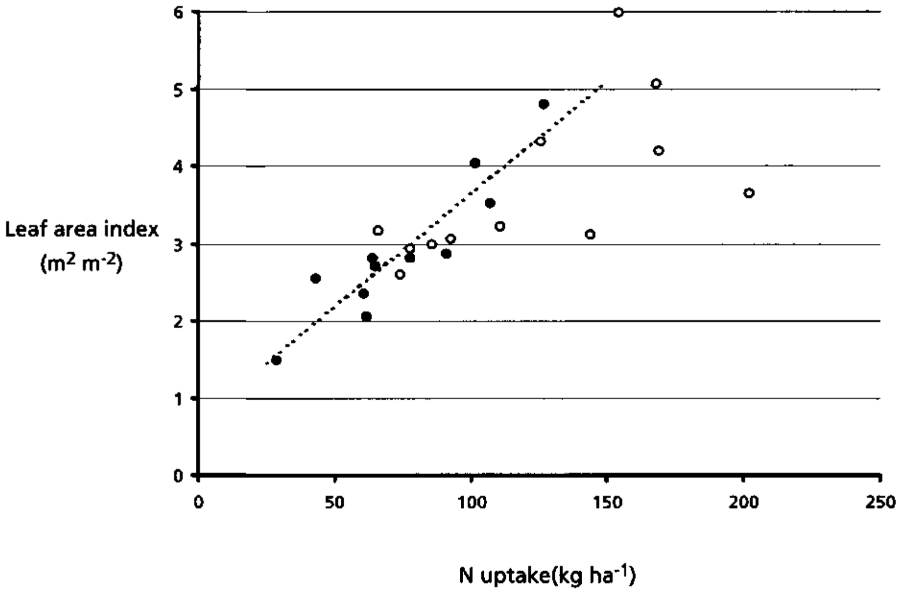

Figure 1.6. Relationship between the whole-plant N uptake and leaf area index in N deficient (●) and non-deficient (O) silage maize (combined data from Schröder *et al.*, 1994; 1995).

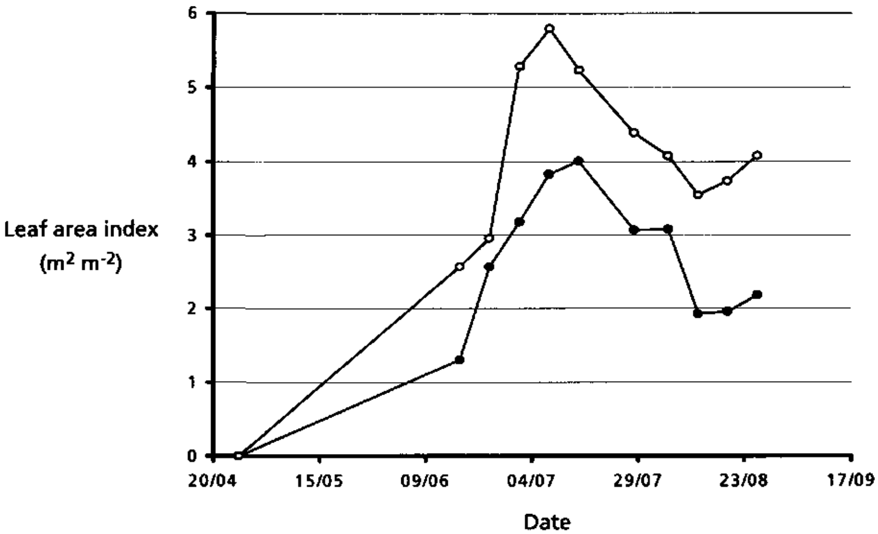

Figure 1.7. Time course of the leaf area index of N deficient (●) and non-deficient (O) silage maize (Schröder & Ten Holte, 1993).

effect on photosynthesis, N also indirectly affects RUE, as N deficient crops tend to allocate a larger fraction of the photosynthates to the roots at the expense of the harvestable plant fraction (Grobbelaar, 1963; Thom & Watkin, 1978; Anderson, 1988; Engels & Marschner, 1990).

Much literature has been published on the response of silage maize to fertiliser N. Many of the references include data on the N uptake, which allow the calculation of the apparent fertiliser N recovery (Van Keulen, 1986). By definition, the apparent N recovery (ANR) is low when more N is applied than the crop needs (Greenwood *et al.*, 1989). Hence, only trials including suboptimal N rates will enable a correct crop-specific ANR to be estimated. Data from Iversen *et al.* (1985b), Meisinger *et al.* (1985), Schröder (1985b; 1985c), Jokela & Randall (1989), Timmons & Baker (1991), Salardini *et al.* (1992) and Jokela (1992a) include at least two of these suboptimal N rates (i.e. with a marginal response of 5 kg silage DM per kg N, representing the current price ratio of silage and fertiliser). Analysis of these data indicates that the median value of the ANR at the N rate beyond which the increase in the DM yield is less than 5 kg per kg N (ANR_{opt}), is 47%. This is close to the 50% that Osmond *et al.* (1992) considered to be typical for optimally managed maize crops. The ANR at suboptimal N rates (ANR_{sub}) is larger in 16 of the 17 trials analysed. Its median value is 58%. ANRs show a large variation at both optimal and suboptimal N rates and, consequently, suboptimal N rates are not a guarantee of high recoveries (Table 1.2). Such an increase in the ANR at suboptimal N rates is uncommon in cereals and grasses (Prins *et al.*, 1988), but has earlier been reported for potatoes by Neeteson *et al.* (1987) and for vegetables by Greenwood *et al.* (1989). They attributed this to the uneven initial root distribution. Silage maize is planted at a row spacing of 0.7-0.8 m and therefore maize rooting patterns have more in common with those of potatoes and vegetables than with those of cereals and grasses. Storage of N in roots and stubble is an unlikely explanation for the relatively low ANR of maize, as roots and stubble generally contain less than 10-25 kg N ha^{-1} and this amount does not show any relationship with the fertiliser N input (Thom & Watkin, 1978; Anderson, 1988; Eghball & Maranville, 1993).

In addition to the uneven distribution of roots, soil fertility may also be unevenly distributed. Soil heterogeneity increases crop N requirements per unit of area and may then seriously depress the recovery of N (De Willigen *et al.*, 1992; Van Noordwijk & Wadman, 1992).

Another explanation for the relatively low ANR values reported may be that the crop's response to N has been analysed with inappropriate regression models. Application of such models may overestimate crop N demand (Neeteson & Wadman, 1987; Sylvester-Bradley *et al.*, 1987; Cerrato & Blackmer, 1990; Bullock & Bullock, 1994; Stecker *et al.*, 1995; Ladewig & Märländer, 1997). Application rates based on an overestimated crop N demand are, by definition, associated with a reduced ANR (Greenwood *et al.*, 1989). A critical analysis of response data is therefore essential if the aim is to avoid the emission of N.

Reducing the N input is an effective measure for reducing the N surplus per unit of area, as apparent N recoveries of maize are low. Reducing the N input could reduce the N surplus per unit of product less than the N surplus per unit of area, however, because more DM is allocated to non-harvested plant fractions.

Production per unit of resource (land, labour, water, energy, pesticide, non-N fertiliser) is likely to decrease if N alone is reduced (De Wit, 1992). Clearly, reducing the N input would be a more acceptable measure if it could be linked to an increase in the N recovery. A comparable yield could then be realised with less N and the N surplus would be less per unit of product, too.

Obviously, there is no clear and simple solution to N related problems associated with maize cropping. To resolve the dilemma between the economically and environmentally best options, the inputs and outputs

Table 1.2. Frequency distribution (expressed as the number of trials) and median value of apparent recoveries (ANR) of spring-applied artificial fertiliser N (%) applied at optimal (ANR_{opt}) and suboptimal (ANR_{sub}) N rates, as observed in 17 trials (references given in text)

Recovery class (%)	ANR_{opt}	ANR_{sub}
< 34	4	3
35-49	8	4
50-64	2	4
65-79	1	2
80-94	1	2
> 95	1	2
median ANR	47	58

associated with the various ways of growing maize need to be accurately quantified. Anyone contemplating growing maize should perform this exercise to find out which combination of crops and production techniques is most profitable, given the environmental constraints operating on the farm. Van de Ven (1996) has developed a mathematical model to explore the potential for environmentally safe dairy farms in The Netherlands and to support such decision making. Models of this type can only be relied upon if the input-output relationships they contain are empirically validated. This means that field experiments are needed.

1.4 Objectives and organisation of the research

As demonstrated above, the maize cropping technique current in The Netherlands is associated with a low recovery of N by the crop and serious losses of N to the environment. It is clear that the low recovery is partly attributable to the high N input, but it is unclear to what extent the high input is necessary for high maize yields. This thesis aims to increase our understanding of the causes underlying the low recovery of N. Its main objectives are therefore:

- to identify and to increase our understanding of *factors* that determine the partitioning of N inputs over crop and losses, with emphasis on maize grown on sandy soils in The Netherlands,
- to provide *techniques* to improve the N efficiency of maize crops,
- to integrate these techniques into a consistent, comprehensive and environmentally sound N management *system* for maize.

1.5 Synopsis

Techniques for improving the fertiliser use efficiency are generally based on the *amount* of nutrients applied and the method of application, in particular the *placement* and the *timing*. De Willigen & Van Noordwijk (1987) showed how these three aspects may interact in a model developed for maize cropping in the humid tropics. They found that the N requirements ('*amounts*') of maize crops differing in root distributions, appeared to depend strongly on the positioning of fertiliser N ('*placement*') and on N splitting strategies (*'timing'*), illustrating the need for a proper synlocalisation and synchronisation.

The first five chapters following this general introduction are based on field and desk research in which the significance of the three aspects was evaluated. Chapters 2 and 3 pertain to the temporal and spatial distribution of maize roots and its implications for the availability of nutrients. Hence, synchronisation and synlocalisation are both issues in these chapters. Chapter 2 (*Soil mineral nitrogen availability to young maize plants as related to root length density distribution and fertiliser application method*) is based on four experiments in the Wageningen Rhizolab. In these experiments the temporal and spatial distribution of maize roots was monitored fortnightly using minirhizotrons. Each experiment included three horizontal positionings of fertiliser N. Effects on maize yields and N recovery were determined. Chapter 3 (*Response of silage maize to placement of cattle slurry*) discusses five field experiments examining the effects of the placement of manure on maize yield and N recovery. The experiments included treatments in which maize was planted either 10 cm away from the slurry injection slots or at random positions.

Chapters 4, 5 and 6 focus on synchronisation. Chapter 4 (*Effects of nitrification inhibitors and time and rate of slurry and fertiliser N application on silage maize yield and losses to the environment*) addresses the consequences of postponing slurry applications from late summer or winter to early spring. The effects in terms of maize yields and losses of N were compared in eight field trials. Chapter 5 (*Effect of split applications of cattle slurry and mineral fertiliser N on the yield of silage maize in a slurry-based cropping system*) focuses on optimizing the timing of applications within the growing season. This chapter evaluates the effects of post-emergence applications of either cattle slurry or artificial fertiliser N, as observed in nine field trials. Chapter 6 (*Effects of cover crops on the nitrogen fluxes in a silage maize production system*) reports on the ability of cover crops to intercept residual soil mineral N and to carry it over to the next growing season. N fluxes of cropping systems varying in N inputs and in winter soil treatment, were monitored for seven consecutive years.

The last three chapters synthesise the results from previous chapters by addressing the relationships between the amount of N applied and the amount ultimately available in the soil and in the crop. Chapter 7 (*Modelling the residual N effect of slurry applied to maize land on dairy farms in The Netherlands*) explores the long-term consequences of excessive manure

applications during the last 25 years. In this study a model on organic N dynamics was calibrated with measured data from a long-term field experiment. Subsequently, the effects of various N management scenarios, including one representing the estimated actual use of manure, were evaluated. Chapter 8 (*Effects of N application on agronomic and environmental parameters in silage maize production on sandy soils*) aims to formulate a general relationship between available N and yield and emission of N. In this chapter data were used from the trials described in the Chapters 4, 5 and 6 and from trials reported by Schröder & Ten Holte (1996).
In Chapter 9 (*General discussion*) an attempt is made to synthesise the findings, relating 'amount', 'placement' and 'timing', and to describe an environmentally sound N management system for maize crops, tuned to sandy soils in The Netherlands.

Note

Chapters 2, 3, 6 and 7 have been or are about to be published in the Netherlands Journal of Agricultural Science. Chapter 4 has been published in Fertilizer Research. Chapter 5 is about to be published by Nutrient Cycling in Agro-ecosystems. Chapter 8 is accepted with minor revisions by Field Crops Research. The reference lists from these individual papers have been amalgamated into one list at the end of this thesis. I thank the editorial boards of Fertilizer Research, Nutrient Cycling in Agro-ecosystems, Netherlands Journal of Agricultural Science and Field Crops Research for their permission to include the papers in this thesis.

CHAPTER 2

SOIL MINERAL NITROGEN AVAILABILITY TO YOUNG MAIZE PLANTS AS RELATED TO ROOT LENGTH DENSITY DISTRIBUTION AND FERTILISER APPLICATION METHOD

J.J. Schröder, J. Groenwold and T. Zaharieva

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2.1 Abstract

Minirhizotron observations from 4 experiments with maize in the Wageningen Rhizolab showed strong vertical and lateral root length density gradients during the first 9 weeks after emergence.

Root length density (Lrv), as determined in core samples 9 weeks after emergence, was positively related (P<0.01) to the number of roots counted concurrently on minirhizotron walls (n). Lrv/n ratios were 1.13, 1.76, 0.99 and 1.21 cm cm^{-1} in the successive experiments.

Subsequently, root numbers counted on previous dates in each experiment, were converted into root length density values and related to thermal time. According to this relation, the average vertical root extension rates were 0.7 and 1.1 cm d^{-1} at temperatures of 13 and 16°C, respectively. Corresponding values for the lateral extension rate were 1.0 and 1.6 cm d^{-1}.

Calculations indicated that the nitrogen (N) content of a 9 weeks old maize crop could generally not be explained by mass flow only. Transport distances between roots and mineral N in the soil, may thus have restricted the availability of N as suggested by preferential uptake of mineral N from soil compartments with a high root length density. The recovery of N was only slightly improved by fertiliser N positioning close to the plant as compared to broadcast N or placement of N halfway between the rows. Recoveries based on the difference method and the isotopic dilution method, yielded similar values. Dry matter yields were not significantly affected by the application method of N. Apparently, the root extension rate and the initial availability of N in the soil prior to the application of fertiliser-N, were sufficient to cover shoot demand under the prevailing circumstances.

Keywords: fertiliser placement, minirhizotron, nitrogen recovery, root length density, *Zea mays* L.

2.2 Introduction

Lack of synlocalisation of nutrients and roots may limit the uptake of nutrients and crop production (De Willigen & Van Noordwijk, 1987). Under these conditions, high nutrient concentrations in the bulk soil are required to maintain a gradient-driven transport to the root surface. Young maize (*Zea mays* L.) crops generally respond positively to high rates of nitrogen (N) application. We hypothesise that this may be attributed to an insufficient synlocalisation due to the current row width (70-80 cm) and a slow lateral and vertical extension of the root system. Circumstantial evidence is provided by the positive response of the dry matter (DM) yield of maize to a row application of N (Touchton, 1988; Maidl, 1990; Maddux *et al.*, 1991; Sawyer *et al.*, 1991).

Lack of synlocalisation may be more likely at low temperatures as they restrict specific root length (i.e. length of roots per unit DM invested), root growth rate, root activity and rooting depth (Ketcheson, 1968; Clarkson & Gerloff, 1979; Engels & Marschner, 1990; Barber & Kovar, 1991; Tardieu & Pellerin, 1991; Richner, 1992), as well as the mineralisation rate (Addiscott, 1983). Hence, low temperatures may have a negative effect on the actual uptake of N. Shoot demand for N, however, is also reduced by low temperatures via effects on both the subterranean shoot meristem and aerial plant parts (Miedema, 1982). Yet, root systems may be less able to satisfy shoot demand in a cold spring, especially as the soil temperature lags behind the air temperature at that stage.

To test this hypothesis root observations in the juvenile stage are required. Reported root data generally refer to times around anthesis and focus on root length density gradients with depth rather than with lateral distance. To fill this gap in knowledge four rhizolab experiments were carried out in 1992 and 1993. These experiments were set up to describe the spatial root development as a function of thermal time and to study the interactions between N placement, distributions of mineral N in the soil and roots, N recovery and maize DM-production. Concomitantly, we used the experiments for a comparison of two calculation methods of the N recovery.

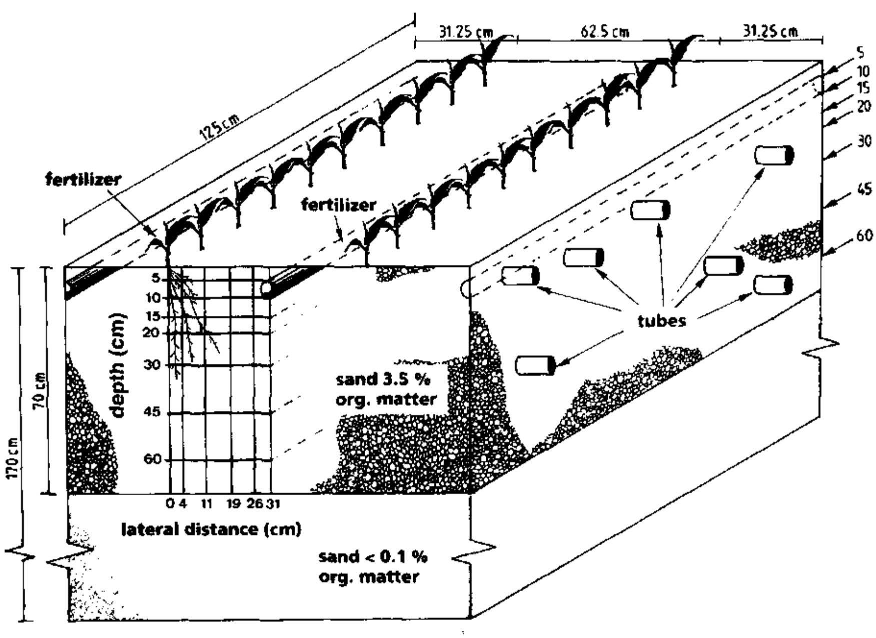


Figure 2.1. Positioning of maize plants, minirhizotron tubes, fertiliser bands (IR-treatment only) and imaginary compartments in the Wageningen Rhizolab.

2.3 Materials and methods

2.3.1 Rhizolab

Four experiments (Experiments 1 and 2 in 1992, Experiments 3 and 4 in 1993) were carried out in four 1.70 m deep, 1.25 x 1.25 m units of the Wageningen Rhizolab. Detailed information on this facility is given in Van de Geijn *et al.* (1994), Smit *et al.* (1994) and Schröder *et al.* (1994). Rhizolab units were filled with a sandy soil with organic matter contents of 3.5 and <0.1% for the upper 70 and 70-170 cm layers, respectively, while 7 cylindrical minirhizotrons (diameter 6 cm) were horizontally installed, perpendicularly to the plant rows at depths of 5, 10, 15, 20, 30, 45 and 60 cm (Figure 2.1). Concurrently, capacitance moisture sensors and nutrient sampling devices were allocated to positions exactly below the plant rows and halfway between them, at depths of 5, 15, 25, 40, 60, 85, 115 and 150 cm. The soil was recompacted layerwise to a constant bulk density of 1.4 and 1.6 kg dm^{-3} throughout the upper 70 and 70-170 cm, respectively. Soil material for the upper 20 cm was mixed with fertilisers equivalent to rates of 45 kg P and 250 kg K ha^{-1} in each experiment. At the end of each experiment, the soil was removed from the units and the filling procedure was repeated for the next experiment. The excavated soil from Experiments 1 and 2 was thoroughly sieved, mixed, stored and re-used for Experiments 3 and 4.

2.3.2 Crop husbandry

Two rows of maize (*Zea mays* L. cv. LG 2080 for the first two, cv. Mandigo for the subsequent two experiments) were planted at a depth of 4 cm and a distance of 62.5 cm on 15th April 1992, 3th July 1992, 15th April 1993 and 1st July 1993 in each rhizolab unit. Stands were thinned to 12.8 plants m^{-2} soon after emergence. Crops were kept weed-free manually, sprayed against pests when necessary and harvested at about 9 weeks after emergence.

2.3.3 Weather conditions

Average daily air temperature measurements were recorded at a weather station 1 km away from the Rhizolab and amounted to 14.1, 17.9, 14.6 and 15.5°C for the period between emergence and harvest for Experiments 1, 2, 3 and 4, respectively. Soil temperatures were collected with thermocouples installed at depths of 5, 15, 25, 40 and 60 cm.
Precipitation was excluded by a transparent shelter covering all rhizolab units during rainfall events. Units were irrigated manually during the first 18-48 days and automatically for the remaining period with a 10 x 20 cm grid drip irrigation system to maintain a moisture content of 0.15-0.19 cm^3 cm^{-3} in the upper 70 cm. Averaged over experiments, measured evapotranspiration amounted to 1-2, 1.5-2.5 and 2-3 mm d^{-1} for the periods 1-3, 4-6 and 7-9 weeks after emergence, respectively. Transpiration was deduced from this by assuming that soil evaporation contributed half to evapotranspiration with a maximum of 0.5 mm d^{-1}.

2.3.4 Root observations

Root observations were made fortnightly and refer to the number of roots per unit area at 2.5 cm intervals along the interface of the bulk soil and the upper side of glass walls of the minirhizotrons. Root length densities were assessed at the end of each experiment in core samples taken in triplicate to a depth of 70 cm with 10 cm increments and 3 lateral positions (viz. in the row, halfway between the rows and half way between these two positions). Soil and roots were carefully separated by soaking. Subsequently, total root length was determined with the line intersect method (Tennant, 1975). Root length density values (Lrv's) were related to the corresponding number of roots on the minirhizotron walls (n) at the end of each experiment according to a linear response without intercept. The association of minirhizotron tubes and soil layers from which the core samples were taken, was adopted from Smit *et al.* (1994). Lrv/n ratios were used to convert minirhizotron observations collected in the course of the experiment into root length densities. Five lateral distance classes (0.00-3.75, 3.75-11.25, 11.25-18.75, 18.75-26.25, 26.25-31.25 cm) and seven depth positions were defined resulting in 35 compartments (Figure 2.1). Observations from the four experiments were pooled per compartment and plotted against thermal time (TT) which was defined as the accumulated average daily temperature (depth 15 cm, threshold (Jones & Kiniry, 1986) 8°C) after emergence. Thermal time ranged from 0 to 700 degree-days. Data were fitted with a linear response model, allowing for a thermal time lag (LAG) needed to arrive in a certain compartment at lateral distance i and depth j (Equation 1).

$$Lrv_{i,j} = 0 \text{ if } TT < LAG_{i,j}, \text{ else}$$

$$Lrv_{i,j} = c_{i,j} \times (TT - LAG_{i,j}) \text{ with} \qquad (1)$$

$c_{i,j}$: constant relating the root length density (Lrv) to TT in compartment i,j

2.3.5 Treatments

Treatments consisted of a control without N fertiliser (C) and three methods of application of 50 kg N ha^{-1}: banded at a depth of 7 cm halfway between the rows (IR), broadcast and mixed through the upper 10 cm layer (BC) or banded at a depth of 7 cm, 4 cm from each row (R). Treatments were randomly allocated to units in each experiment. ^{15}N depleted (999.9 g ^{14}N kg^{-1}) ammonium nitrate and ammonium sulphate, were used in 1992 and 1993, respectively.

2.3.6 Measurements

Concentrations of mineral N (ammonium-N and nitrate-N) in the soil solution were assessed every three weeks, from planting until about 9 weeks after emergence, with ceramic cups and porous Rhizon SS tubes (Meijboom & Van Noordwijk, 1992) and divided by the concomitantly measured moisture content to calculate the mineral N quantities per unit soil volume. ^{15}N atom % in the soil solution was assessed at the start and end of each experiment.
Crops were harvested about 9 weeks after emergence and split into stems and leaves. Fresh weight of the fractions and their dry matter content were determined after drying for 24 h at 105°C. Leaf area of all plants was assessed photoanalytically. Dried material was analysed for total N content and ^{15}N atom %.

Mineral N in the soil solution and total N in leaves and stems were determined with a TRAACS 800 continuous flow analysis system (Bran Luebbe Analyzing Technologies). ^{15}N atom % in soil solution and crops were assessed with a gas specific mass spectrometer (Europe Scientific).

2.3.7 Nitrogen recovery

N recoveries were calculated according to the difference method (Van Keulen, 1986; Equation 2) and according to the isotopic dilution method (Varvel & Peterson, 1990; Equation 3).

N recovery (%) = (SN (or SMN_{70}) of fertilised crop, kg ha^{-1} -
SN (or SMN_{70}) of unfertilised crop, kg ha^{-1}) /
(0.01 x N rate, kg ha^{-1}) 2

N recovery (%) = ((atom % ^{15}N in SN (or SMN_{70}) of unfertilised crop) -
(atom % ^{15}N in SN (or SMN_{70}) of fertilised crop)) x
(SN (or SMN_{70}) of fertilised crop, kg ha^{-1}) /
((0.01 x N rate, kg ha^{-1}) x (natural atom %
^{15}N - atom % ^{15}N in depleted fertiliser)) 3

with SN = N stored in maize shoot, SMN_{70} = N stored as mineral N in the upper 70 cm soil layer, natural atom % ^{15}N = 0.3663.

2.4 Results

2.4.1 Roots

Except during the pre-emergence period of the early planted maize crop in 1992 (Experiment 1), ambient temperatures were too high to induce any serious cold stress. In early planted crops, the soil temperature decreased with depth in both years (Figure 2.2). Root length densities determined in core samples about 9 weeks after emergence, showed steep gradients in

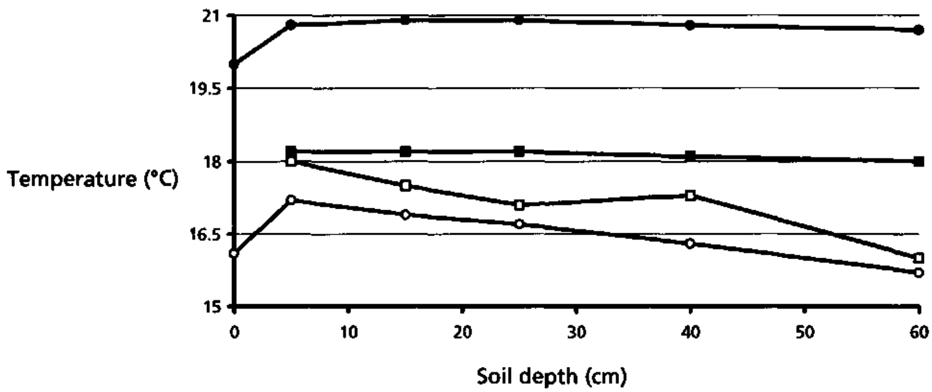


Figure 2.2 Average daily temperature (°C) at various soil depths (—O— = early planted experiment, 1992; —●— =late planted experiment 1992, —□— = early planted experiment, 1993; —■— = late planted experiment, 1993).

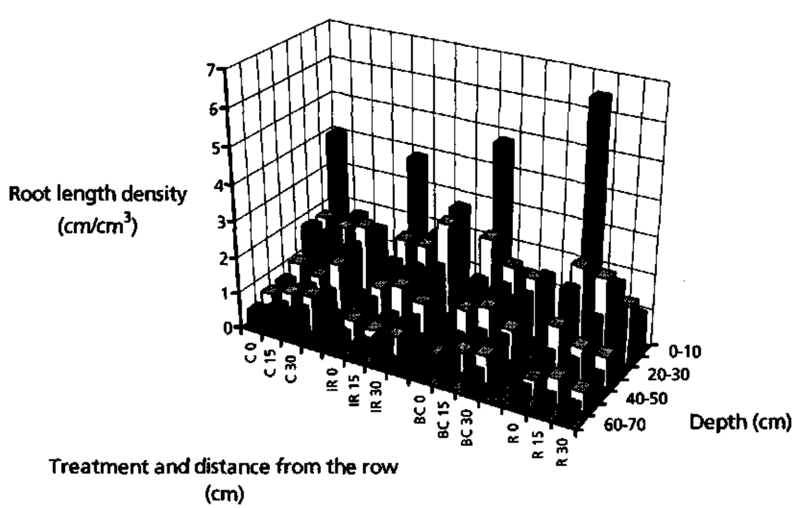


Figure 2.3. Root length density in core samples about 9 weeks after emergence in relation to depth, lateral distance from the row and N fertiliser application method (C=control, IR=fertiliser placed halfway between the rows, BC=broadcast fertiliser, R=fertiliser placed near the row).

both vertical and lateral direction. Vertical gradients were strongest in the row, lateral gradients were strongest in the upper soil layers. (Figure 2.3). N fertiliser placement between the rows resulted in significantly ($P<0.05$) larger root length densities in the upper 20 cm soil layer halfway between the rows and lower root length densities in their vicinity as compared to the BC and R treatment. In the upper 20 cm, root length densities of the control treatment were relatively low compared to the BC and R treatment, whereas they were slightly higher halfway between the rows, especially in deeper layers (Table 2.1).

Adjusted correlation coefficients (R^2_{adj}, Montgomery & Peck, 1982) of the regression model relating root numbers in minirhizotrons (n) to root length densities (Lrv) in core samples amounted to 0.48, 0.16, 0.11 and 0.29 in the subsequent experiments. Corresponding Lrv/n ratios were 1.13, 1.76, 0.99 and 1.21 ($P<0.01$), respectively. Lrv/n ratios differed significantly ($P<0.05$) among experiments, except for Experiments 1 and 4. Extension of the regression model with a factor accounting for the lateral distance, changed R^2_{adj} with only -0.02 to +0.04 (absolute). Taking depth into account, improved the R^2_{adj} only in the late planted experiment of 1992. As trends

Table 2.1. Average root length density (cm cm^{-3}) 9 weeks after emergence in the 0-20 and 50-70 cm soil layers in relation to lateral distance from the row and N fertiliser application method.

Depth (cm)	Lateral distance (cm)	Treatment:*			
		C	IR	BC	R
0-20	0	2.9 a**	2.9 a	3.6 b	4.4 c
0-20	15.5	1.7 a	1.8 a	1.6 a	1.9 a
0-20	31***	1.7 ab	2.6 a	1.5 b	1.3 b
50-70	0	0.6 a	0.6 a	0.5 a	0.5 a
50-70	15.5	0.8 a	0.5 b	0.8 a	0.6 ab
50-70	31	0.9 a	0.7 ab	0.6 b	0.5 b

* C=control, IR=N placed halfway between the rows, BC=broadcast N, R=N placed near the row

** different letters within a row indicate significant differences between treatments at the $P<0.05$ level

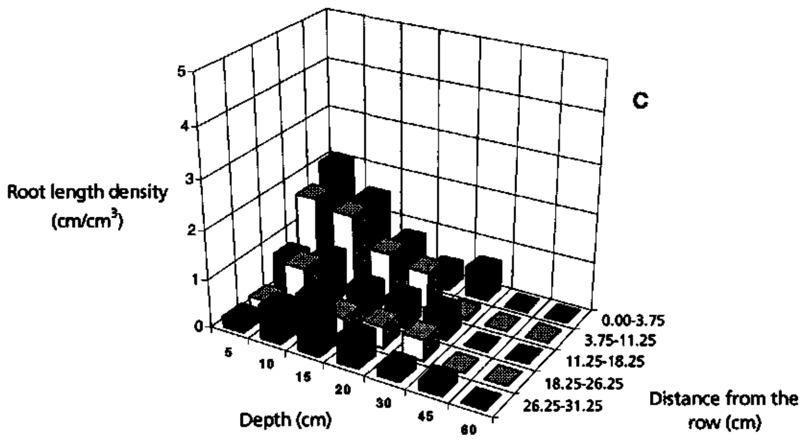
*** halfway between rows

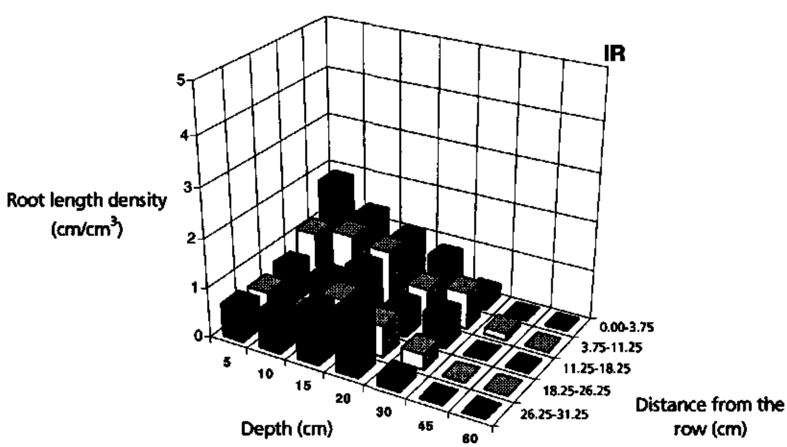
Table 2.2. Depth-dependent time lag (LAG, °Cd) and ratio (c, cm °Cd^{-1} cm^{-3}) and R^2_{adj} for the soil compartment-specific relation between thermal time (TT, °Cd, threshold 8°C) after emergence and root length density of maize during juvenile growth stages.

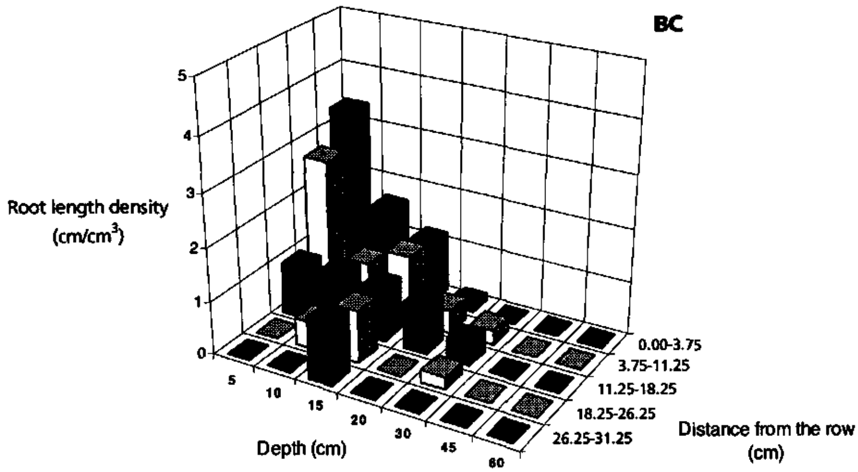
Treatment	Lateral distance class (cm)	LAG for various depths (cm)							c x 1000	R^2_{adj}
		5	10	15	20	30	45	60		
C	0.00 - 3.75	0	108	248	323	281	403	593	5.144	0.67
	3.75 - 11.25	3	44	179	223	390	452	507	4.283	0.76
	11.25 - 18.75	219	176	271	274	275	419	418	4.193	0.65
	18.75 - 26.25	343	119	310	293	297	435	434	4.140	0.41
	26.25 - 31.25	338	211	87	248	343	350	427	3.704	0.42
IR	0 - 3.75	0	82	148	199	331	467	500	4.613	0.79
	3.75 - 11.25	88	45	76	238	195	364	466	3.596	0.74
	11.25 - 18.75	187	195	77	240	218	426	403	3.540	0.67
	18.75 - 26.25	177	271	69	172	287	722	487	2.816	0.62
	26.25 - 31.25	256	235	175	123	360	722	724	4.731	0.61
BC	0 - 3.75	0	207	262	383	442	667	570	8.380	0.64
	3.75 - 11.25	3	266	215	338	361	483	513	6.800	0.72
	11.25 - 18.75	188	166	186	208	311	443	503	4.641	0.60
	18.75 - 26.25	487	294	187	440	351	425	667	4.668	0.46
	26.25 - 31.25	414	507	189	448	472	652	722	5.496	0.42
R	0 - 3.75	0	116	365	394	497	512	520	11.601	0.87
	3.75 - 11.25	0	77	206	240	315	435	490	6.470	0.75
	11.25 - 18.75	158	177	227	174	290	380	448	5.139	0.60
	18.75 - 26.25	269	452	154	275	389	439	447	5.624	0.61
	26.25 - 31.25	425	378	116	198	261	410	445	4.893	0.42

* C=control, IR=N placed halfway between the rows, BC=broadcast N, R=N placed near the row

between Lrv/n ratios and distance or depth were absent, an identical value for all depths and lateral distances was used for the conversion of minirhizotron observations into root length densities within one experiment. Highly significant (R^2_{adj} 0.41 - 0.87) relationships were found between thermal time and the root length density, using the lateral distance as a factor in


C
Root length density
(cm/cm³)
0
1
2
3
4
5
5
10
15
20
30
45
60
Depth (cm)
0.00-3.75
3.75-11.25
11.25-18.25
18.25-26.25
26.25-31.25
Distance from the
row (cm)


IR
Root length density
(cm/cm³)
0
1
2
3
4
5
5
10
15
20
30
45
60
Depth (cm)
0.00-3.75
3.75-11.25
11.25-18.25
18.25-26.25
26.25-31.25
Distance from the
row (cm)



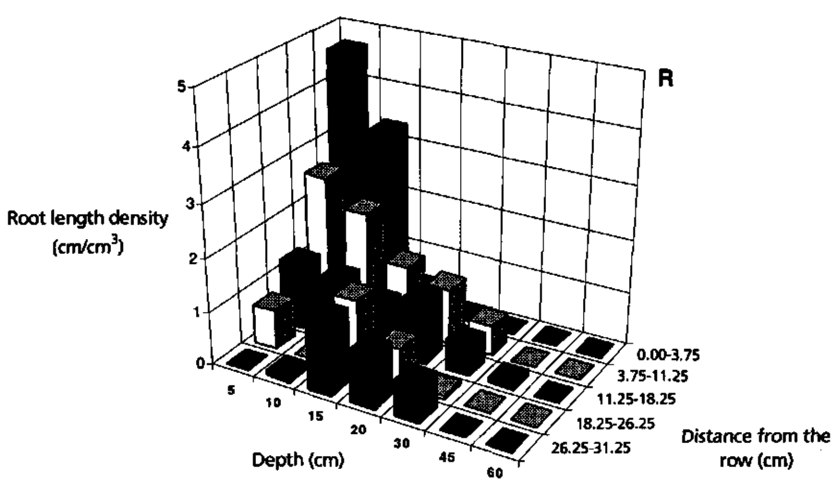


Figure 2.4. Calculated root length density after 400 degree-days after emergence (base temperature 8°C) in relation to depth, lateral distance from the row and N fertiliser application method (C=control, IR=fertiliser placed halfway between the rows, BC=broadcast fertiliser, R=fertiliser placed near the row).

the model (Table 2.2). Allowing c_{ij} to vary with depth as well, changed the R^2_{adj} with -0.01 to +0.09 (absolute). Obviously, LAG $_{ij}$ increased with depth and lateral distance. Using calendar time instead of thermal time yielded R^2_{adj}'s that were 0.04-0.07, 0.04-0.11, 0.16-0.19, 0.09-0.22 and 0.11-0.19 lower (absolute) for the consecutive lateral distance classes, respectively. Figure 2.4 illustrates the root length density distribution at 400 degree-days (e.g. after 50 days with a temperature of 16°C) after emergence. At that stage the upper 10 cm between the rows was still unexploited in the BC and R treatment and only slightly occupied by roots in the C and the IR treatment.
In none of the treatments, roots extended beyond a depth of 45 cm and 26-49% of the 35 defined compartments were as yet unexploited.

2.4.2 Nitrogen

Mineral N in the upper 70 cm soil layer of the control treatments at the start of Experiments 1, 2, 3 and 4 amounted to 32, 142, 138 and 184 kg ha^{-1}, respectively. In all four experiments the amounts of soil mineral N in the control treatments remained more or less constant during the first 2-4 weeks after planting, indicating that N uptake by the crop and net mineralisation (= gross mineralisation minus losses including immobilisation) were in balance. Subsequently, uptake exceeded net mineralisation so that N was gradually depleted starting from the upper layers. Balance sheet calculations indicated that the net mineralisation during the full growing period (= shoot N + soil mineral N at harvest - soil mineral N at planting) of Experiments 1, 2, 3 and 4 amounted to 32, -13, 5 and 9 kg N ha^{-1}, respectively.
Depletion also showed a gradient in the horizontal plane, as illustrated by the difference in the dynamics of soil mineral N between positions in the row and between the rows during the period from 30 to 50 days after emergence. In the upper 30 cm, N tended to be taken up preferentially from compartments in the row as shown by the difference in change of the supply of soil mineral N in the row and halfway between the rows (Figure 2.5A), whereas in the 30-70 cm layer, a tendency for preferential N uptake from compartments between the rows was observed (Figure 2.5B).
Horizontal soil moisture gradients were not observed in any of the experiments (Schröder *et al.*, 1994).

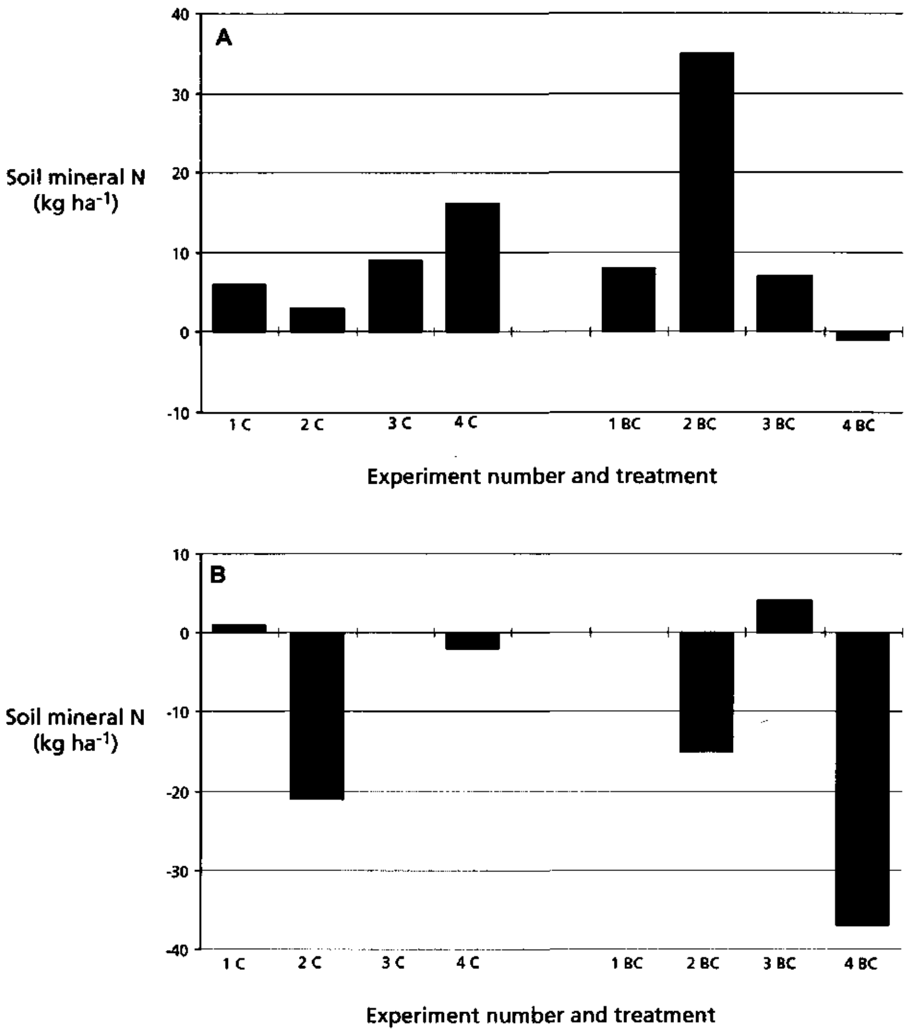


Figure 2.5. Difference in the dynamics of mineral N in the soil in (A) the 0-30 cm layer in the row and halfway between the rows and in (B) the 30-70 cm layer in the row and halfway between the rows, during the period from 30 to 50 days after emergence (C=control, BC=broadcast fertiliser); note: positive values indicate preferential uptake from below the row, negative values from between the rows.

Table 2.3. Leaf area index (LAI), leaf N concentration and shoot dry matter, shoot N yield and recovery of fertiliser N in maize shoots and in shoots and soil (0-70 cm soil layer) together according to the difference and isotopic dilution methods, about 9 weeks after emergence (averaged over experiments).

Treatment	LAI	Leaf N	Shoot		Recovery (%)			
		concentration	DM	N	difference method		isotopic dilution	
	(m^2 m^{-2})	(g 100 g^{-1})	(kg ha^{-1})	(kg ha^{-1})	shoot	shoot+soil	shoot	shoot+soil
C*	3.3 a **	3.29 a	2983 a	81 a	-	-	-	-
IR	3.5 ab	3.42 a	3322 ab	99 b	36 b	96 a	40 a	66 a
BC	3.4 ab	3.40 a	3319 ab	93 b	24 a	85 a	36 a	58 a
R	3.6 b	3.40 a	3599 b	101 b	40 b	103 a	54 b	79 b

* C=control, IR=N placed halfway between the rows, BC=broadcast N, R=N placed near the row

** different letters within a row indicate significant differences between treatments at the *P*<0.05 level

Leaf area, leaf N concentration and shoot dry matter yield generally showed a positive response to N application, without significant effects of the fertiliser application method. Both R and IR were superior to BC in 2 out 4 experiments with respect to shoot dry matter.

Shoot N yields were slightly larger when N was applied close to the row (R) in 3 out of 4 experiments but the effect was not significant when averaged over experiments (Table 2.3). N recoveries according to both Equation 1 and 2, were largest for the R-treatment and significantly different from the BC-treatment. Averaged over experiments, shoot N recovery rankings were similar for the difference and the isotopic dilution method. Absolute values according to the isotopic dilution method were larger in Experiment 3, only.

Averaged over experiments, the fraction of the fertiliser recovered as soil mineral N, calculated according to a given method, hardly varied among treatments. Values of this fraction derived from the isotopic dilution method were always substantially lower than those based on the difference method.

As for the summed recovery of shoot N and soil mineral N, substantial amounts of fertiliser N were not accounted for when the isotopic dilution method was used, especially for broadcast N. Based on the difference method, a large part of the fertiliser N was not recovered in shoot or soil in Experiment 1, whereas a substantial gain in soil mineral N was observed in Experiment 4.

Table 2.4. Accumulation of N in the shoot, calculated contribution from mass flow and from diffusion and interception (kg N ha^{-1}) and the relative proportion of diffusion and interception in the accumulated N.

	Experiment							
	1		2		3		4	
treatment*	C	BC	C	BC	C	BC	C	BC
mass flow (kg ha^{-1})	12	27	39	71	51	52	64	67
diffusion+interception (kg ha^{-1})	31	35	88	90	40	30	0	0
diffusion+interception (%)	72	56	69	56	44	37	0	0

* C=control, BC=broadcast N

The relative contribution of mass flow to N uptake of maize during the first 9 weeks after emergence can be approximated by multiplying the transpiration rate and the average mineral N concentrations in rooted layers between successive samplings. The results of these calculations indicated that even in fertilised treatments substantial amounts of N must have originated from diffusion or from interception by extending roots, except in Experiment 4 (Table 2.4).

2.5 Discussion

2.5.1 Roots

In 1992 and 1993 we carried out four experiments in the Wageningen Rhizolab to examine whether the recovery of N by maize can be explained in terms of the spatial and temporal distribution of its root system. As low soil temperatures may restrict N availability, two of the experiments were planted in early spring in order to evoke cold stress. We did not obtain stress, however, as the temperature was substantially higher than normal and initial supplies of soil mineral N were large.

The observed ratios between root length density values and the observed number of intersections on minirhizotron walls (Lrv/n), were all substantially lower than 2, the value expected for randomly growing roots (Melhuish &

Lang, 1968; Lang & Melhuish, 1970). This may indicate preponderance of vertically growing roots. Chaudhary & Prihar (1974) and Tardieu & Pellerin (1991) found that low temperatures caused a reduced vertical extension of maize roots which would result in a negative relation between temperature and the Lrv/n ratio. In our experiments, however, a positive relation ($P<0.05$) was observed between the Lrv/n ratio and average daily soil temperature. Maybe other factors such as the loss of fine roots during the processing of core samples, may have contributed to the relatively low Lrv/n ratios.

Root length densities were closely related to thermal time during juvenile growth stages (ranging from 0 to 700 degree-days). From these relations can be calculated that roots would have penetrated to a depth of 60 cm within 81-101 days after emergence at a temperature of 13°C and within 50-63 days after emergence at a temperature of 16°C, suggesting growth rates of 0.6-1.2 cm d^{-1} which is close to the results of Foth (1962) and De Willigen & Van Noordwijk (1987). At temperatures of 13 and 16°C, respectively, it would take another 16-85 and 10-54 days to achieve a root length density of at least 0.5 cm cm^{-3} at any lateral position at a depth of 60 cm. Likewise, it can be calculated that the first roots arrive at lateral distance of 26-30 cm within 17-38 and 11-24 days after emergence at temperatures of 13 and 16°C, respectively, equivalent to lateral extension rates of 0.7-2.5 cm d^{-1}. These values are in good agreement with the range of 14-50 days after emergence that can be derived from the combined data of Foth (1962), Chaudhary & Prihar (1974), Mengel & Barber (1974) and De Willigen & Van Noordwijk (1987). It must be emphasised, however, that the proposed calculation of root extension rates at different temperatures, is merely an approximation, as specific root lengths are positively related to temperature (Kiel & Stamp, 1992). Consequently, extension rates may be smaller at low and larger at high temperatures.

The lateral extension rate was largest where the supply of soil mineral N close to the plant row was low (C and IR). Probably, N placement between the rows has stimulated lateral root extension (Granato & Raper, 1989). The 15-20 cm layer was first exploited by roots. It took another 18-27 and 10-18 days at temperatures of 13 and 16°C, respectively, before the root length density between the rows was at least 0.5 cm cm^{-3}. For shallower layers, at least 72 and 45 days were needed to achieve similar root length densities at temperatures of 13 and 16°C, respectively. Such a slow exploration of the upper inter-row soil volume may limit the efficacy of post emergence N dressings if N is applied as a band dressing between the rows (Jokela & Randall, 1989).

2.5.2 Nitrogen

Mass flow alone could not account for the observed shoot N uptake. Consequently, N must have partly originated from interception and diffusion. In agreement with results of Aufhammer *et al.* (1991), Lorenz (1992) and Schröder & Ten Holte (1995), we observed lateral gradients of soil mineral N supplies, indicating that N taken up from a certain compartment was not instantaneously replenished from neighbouring compartments. N depletion of compartments was positively related to root length density.

Horizontal soil moisture gradients were not observed, suggesting a rapid redistribution of soil water. In a field situation where precipitation does not reach the soil surface as evenly as in the Rhizolab (e.g. Ellies & Huber, 1991; Girardin, 1992), this may be different.

N application generally increased leaf area, leaf N contents and N and DM yields. No significant differences were observed, however, between crops that received N halfway between the row or near the rows. This may have been due to the absence of cold stress even in early planted crops, which may have resulted in a relatively fast root extension. Moreover, root observations indicated that IR applied N, promoted lateral root extension thus compensating for the lack of soil mineral N in the vicinity of the plant. Apparently, there is an interaction between the presence of N and the proliferation of roots. Moreover, the availability of mineral N in our soils was extremely high, probably due to soil manipulation during the incorporation of P and K fertilisers and the filling and emptying of rhizolab units, making the positioning of fertiliser N less relevant. The recyling of the soil from Experiments 1 and 2 with supplies of residual soil mineral N of 28 and 14 kg N ha^{-1} in the upper 70 cm soil layer, respectively, has only slightly increased the availability of N in Experiments 3 and 4.

Drought was avoided in our experiments. This may also explain the absence of significant N placement effects. De Willigen & Van Noordwijk (1995) demonstrated that deficiency of water may reduce the uptake of N through a negative effect on the transport of N in the soil rather than a direct effect on the transpiration. Hence, our results may have been different under dry conditions.

Recoveries derived from isotopic dilution are usually lower than those based on the difference method (Varvel & Peterson, 1990; Timmons & Baker, 1991; Blaylock & Cruse, 1992; Torbert *et al.*, 1993), due to so called added N interactions (Rao *et al.*, 1992). In our experiments, however, both methods yielded similar results. This may imply that isotope substitution has been limited which would have reduced the recoveries obtained with the isotopic dilution method. However, the results of Experiment 4, showing both a larger gain in the supply of soil mineral N than could be explained from fertiliser N input, combined with an average crop plus soil ^{15}N recovery of only 77%, suggested some substitution of ^{15}N in organic matter by ^{14}N from fertiliser. This means that there must be another reason for the fair agreement between recoveries based on the two methods than the absence of isotope substitution. An explanation may be found in an incomplete exploitation of the soil in fertilised crops. This would, by definition, overestimate the contribution of non-fertiliser N to the N uptake of fertilised crops and would underestimate the recovery obtained with the difference method. Indeed, both core samples and minirhizotron observations generally indicated that the extremes of the profile were slightly better exploited by roots in the control than in fertilised treatments. This coincided with smaller amounts of residual soil mineral N in the extreme soil compartments of the control than in corresponding compartments of the treatment where fertiliser N was broadcast.

In Experiments 1, 2 and 3, net N mineralisation in the upper 70 cm soil layer during the full growing period, was lower in the fertilised treatments than in the control, suggesting losses of fertiliser N during the first 9 weeks after emergence. For the BC treatment, these calculated losses amounted to 28 and 34% of the applied fertiliser in Experiments 1 and 3, respectively. Leaching into the 70-170 cm layer was not observed (Schröder *et al.*, 1994), so losses were probably due to denitrification and immobilisation. In Experiment 2, losses of BC fertiliser N were limited to 8%. N enrichment of the 70-170 cm layer (Schröder *et al.*, 1994) indicated that leaching accounted for the minor losses in that experiment. In Experiment 4 net mineralisation in fertilised treatments exceeded that in the control, suggesting a priming effect.

It was concluded that the DM and N yield of 9 weeks old maize crops responded positively to N. The fertiliser placement method had no effect despite a limited root extension during the early crop stage. Shoot N yields were circa 25% larger than what is normally observed 9 weeks after emergence under field conditions, indicating that the absence of placement effects was not due to reduced crop demand for N. Apparently, N transport in the soil was not limiting growth under the current soil temperature and moisture conditions.

CHAPTER 3

RESPONSE OF SILAGE MAIZE TO PLACEMENT OF CATTLE SLURRY

J.J. Schröder, L. ten Holte and G. Brouwer

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3.1 Abstract

Placement of nitrogen (N) or phosphorus (P) fertilisers can improve the efficiency of fertiliser use, reduce the input needed for maximum production, and better balance the nutrient put in with fertilisers and removed with crop products. From this perspective, the effect of the placement of cattle slurry on the dry matter (DM) yield of silage maize was studied in five experiments on sandy soils in 1993 and 1994.

Slurry was injected in spring at a rate of 30 m^3 ha^{-1} in slots 25 cm apart ('standard injection') or in slots 75 cm apart ('banded injection'). Subsequently, maize was planted at a row spacing of 75 cm parallel to the slots, either at random lateral positions in the 'standard injection' treatment or 10 cm next to the injection slots of the 'banded injection' treatment. All treatments, including a control without slurry, were combined with 0 and 20-31 kg ha^{-1} subsurface banded P starter fertiliser.

DM yields of silage maize were on average reduced by 8% when conventionally injected slurry ('standard injected') was not supplemented with a P-starter. However, the yield reduction was limited to 2% when slurry was banded ('banded injection').

Observations on the distribution of soil mineral N and roots in two of the experiments indicated that during the first 5-7 weeks after planting, nutrients were predominantly supplied by the soil volume close to the plant row. This may explain the positive response of maize to placement which was strongest and significant on P-responsive sites, indicating that placement mainly improved the availability of slurry P. Improvements in the availability of slurry N may have played a secondary role.

Our results suggest that slurry placement can minimise the risk of yield loss associated with reduced fertiliser inputs and contribute to a better nutrient balance between fertiliser inputs and removal in crop products.

Keywords: cattle slurry, maize, nitrogen, phosphorus, placement, root distribution

3.2 Introduction

Placement of fertilisers reduces the risks of microbial immobilisation of nitrogen (N) and phosphorus (P), physico-chemical fixation of P and, in case of ammonium, early nitrification into leachable nitrate (Wetselaar *et al.*, 1972), as compared to the broadcast application of fertilisers. When fertilisers are placed close to the root system, placement can further promote a timely interception of nutrients by crops. Maize crops are commonly grown at row spacings of 70-80 cm and can respond markedly to fertiliser placement, probably due to the initially incomplete exploitation of the soil by their roots (De Willigen & Van Noordwijk, 1987; Barber & Kovar, 1991; Schröder *et al.*, 1996a). The first records of a positive response to the placement of P date from the 1950's (De Wit, 1953; Prummel, 1957). More recently, a positive response to the placement of N was reported (Eckert, 1987; Touchton, 1988; Maidl, 1990; Maddux *et al.*, 1991). Such a positive response is most likely at low levels of soil fertility (Jokela, 1992b) and when low soil temperatures reduce mineralisation (Addiscott, 1983), root extension rate and root functioning (Ketcheson, 1968; Mackay & Barber, 1984; Engels & Marschner, 1990). Low soil temperatures occur frequently in spring in Northwest Europe. Hence, most maize growers have their planters equipped with extra coulters enabling them to apply subsurface banded mineral NP-starters and reduce the risk of temporary deficiencies.

In The Netherlands, maize is mainly grown on dairy farms. External inputs of N and P on these farms should be reduced for environmental reasons (Korevaar & Den Boer, 1990). Recently, legislation has been proposed in The Netherlands, putting a levy on the difference between nutrient inputs on a farm and the nutrients taken off through products (Anonymous, 1995). Consequently, the nutrient demand of crops is to be covered with the on-farm produced manure rather than with purchased fertilisers. This requires application techniques for manure which enable a timely availability of nutrients to maize. Sawyer *et al.* (1991) observed a negative relationship between the yield of maize and the lateral distance between the plant rows and the slurry injection slot. Yields were depressed by 8% when maize was planted in between the slots instead of next to the slots. They attributed the effects to the availability of slurry N and considered their results to be an illustration of todays imperfect injection systems. On the other hand the results can be seen as an indication of placement benefits and suggest that slurry placement may be a method to substitute for the commonly used mineral NP-starters. From this perspective we studied the effect of slurry placement on maize yields and investigated whether effects, if any, are due to an enhanced availability of P or N.

3.3 Materials and methods

3.3.1 Experimental setup and crop husbandry

Five experiments, referred to as Experiments I-V, were carried out on sandy soils in 1993 (Experiment I-III) and 1994 (Experiments IV-V). Experiment I took place in Hengelo (52.03° N, 6.18° E). Experiments II and III were located in Wageningen (51.58° N, 5.40° E) and were executed on the same site, as were Experiments IV and V. Maize was planted on April 27, April 16 and April 21 in the Experiments I, II and IV, respectively. Planting in Experiments III and V was postponed to May 27 and June 1, respectively, to evaluate interactions between slurry placement methods and soil temperatures. Soils had fairly similar HCl-extractable K (NEN 6442 procedure) and organic matter (NEN 5754 procedure) contents but differed in their water extractable P (Sissingh, 1971) contents. Soil mineral N contents at the onset of the experiments varied among the sites, showing a relative increase of the N content as the season progressed (cf. II and III, IV and V; Table 3.1).
Two slurry placement methods ('standard injection' and 'banded injection')

Table 3.1. Soil characteristics (0-30 cm).

Year	Site	Planting date	Experiment	Extractable P ($mg\ l^{-1}$)	Extractable K ($mg\ g^{-1}$)	Mineral N* ($kg\ ha^{-1}$)	Organic matter ($kg\ kg^{-1}$)
1993	Hengelo	early	I	14	0.06	15	0.050
	Wageningen	early	II	14	0.08	42	0.036
		late	III	14	0.08	71	0.036
1994	Wageningen	early	IV	23	0.06	22	0.026
		late	V	23	0.06	36	0.026

* NO_3-N and NH_4-N in the 0-60 cm layer of control plot at planting

and a control without slurry were included in each experiment. Cattle slurry was injected at a depth of 10-15 cm and a slot spacing of 25 cm ('standard injection') or 75 cm ('banded injection') after mould board ploughing. Within 2 days after injection, maize (*Zea mays* L., cv. Melody in Experiment I, cv. Mandigo in Experiments II-V) was planted at a row spacing of 75 cm parallel to the injection slots, either randomly with respect to slots 25 cm apart ('standard injection') or 10 cm next to slots 75 cm apart ('banded injection'). These treatments were combined with 0 and 31 (0 and 20 in Experiment I) kg ha^{-1} subsurface banded P-starter fertiliser (triple super phosphate), applied at planting to evaluate interactions between slurry placement methods and the availability of P from sources other than slurry. In the banded slurry treatment P-starter was applied on the opposite side of the maize row.
Slurry was applied at a rate of 30 m^3 ha^{-1} in all five experiments. The nutrient input with the slurry is listed in Table 3.2. The experiments in Wageningen also included standard and banded slurry treatments at a rate of 60 m^3 ha^{-1} combined with 31 kg ha^{-1} starter-P.
A supplementary broadcast mineral fertiliser dressing of 225 kg ha^{-1} K was applied to all treatments of Experiments II, III, IV and V. In 1994 (Experiments IV and V) 45 kg ha^{-1} P was applied as an overall dressing to all treatments in the preceding winter to find out whether placement effects would also occur in the presence of abundant P.
All experiments had a randomised complete block design with 3 blocks in Experiments I, IV and V and 4 blocks in Experiments II and III. Within the blocks, 3 slurry treatments (0 m^3 ha^{-1}, 30 m^3 ha^{-1} 'standard injection', 30 m^3 ha^{-1} 'banded injection' x 2 starter P treatments (with and without)) were included. In Wageningen 2 additional slurry treatments (60 m^3 ha^{-1} 'standard injection' with P-starter, 60 m^3 ha^{-1} 'banded injection' with P-starter) were added. The size of individual plots (slurry x starter treatments) was 15 m x 6 m.

Table 3.2. Nutrient input with 30 m^3 ha^{-1} cattle slurry (kg ha^{-1}).

Year	Experiment	N	NH_4-N	P	K
1993	I	97	47	13	124
	II	122	64	20	129
	III	118	63	20	112
1994	IV	131	62	21	134
	V	138	78	21	151

3.3.2 Measurements

Maize dry matter (DM) yields and N and P uptakes at silage maturity (at approximately 30 percent DM content) were measured by weighing the fresh yield of the inner 10 m x 3 m area of each plot, followed by the determination of the DM content by drying for 24 h at 105°C. In a subsample of the chopped and dried product the total N content was assessed according to Dumas (Macro N, Foss Heraeus) and the P content was assessed colorimetrically (Starrcol) after destruction with H_2SO_4/HNO_3.
Soil mineral N (SMN, including NO_3 and NH_4-N) was assessed after extraction from soil cores with 1 *N* KCl, using a continuous flow analyzer (TRAACS 800, Bran & Luebbe). Samples were taken prior to slurry application and about 10 weeks after planting in 20 cm increments of the upper 60 cm in the control and the standard injected slurry plots of the 60 m^3 ha^{-1} treatment of Experiments II-V. Samples taken before the application of slurry were taken at random positions, post-emergence samples were taken from positions in, next to and between the maize rows. Per treatment and position, 6 core samples were taken and pooled over replicates before analysis.
The distribution of the root system was determined 7 and 5 weeks after planting in the standard and banded slurry plots of the 30 m^3 ha^{-1} treatment (without starter-P) of Experiments IV and V, respectively, and expressed as root length per unit soil volume ('root length density'). Observations were confined to the two inner rows of plots from the second replicate. Root length density was determined by inserting a needle board (width 160 cm x depth 40 cm with 10 cm long needles in a 5 cm x 5 cm grid) to the vertical wall of an inspection trench. The trench was dug within the first 2.5 m of the experimental plot and found itself outside the area from which maize DM yields were derived. The needle board was positioned perpendicularly to the maize rows with its centre in between two rows. The board was removed as a monolith. Subsequently, adhering soil was washed away and total root length per 5 cm x 5 cm x 10 cm volume was determined. Handling and processing are described in detail by Schröder *et al.* (1995). Presented root length density data pertain to the average of the two maize rows enclosed by the needle board.

3.3.3 Definitions

The apparent N recovery of slurry N (ANR) was calculated as the difference of the N uptake of a manured crop and the N uptake of the control (without P-starter) and expressed as a percentage of the total-N input from slurry. The apparent N efficiency of slurry N (ANE) was calculated as the difference of the DM yield of a manured crop and the DM yield of the control (without P-starter) per kg total-N from slurry. The surpluses of N and P of a treatment were defined as the difference between the amounts of total-N and P applied as cattle slurry or starter fertiliser and the amounts exported from the field. Our calculation of the P surplus does not include the broadcast P dressing applied to all plots of Experiments IV and V.

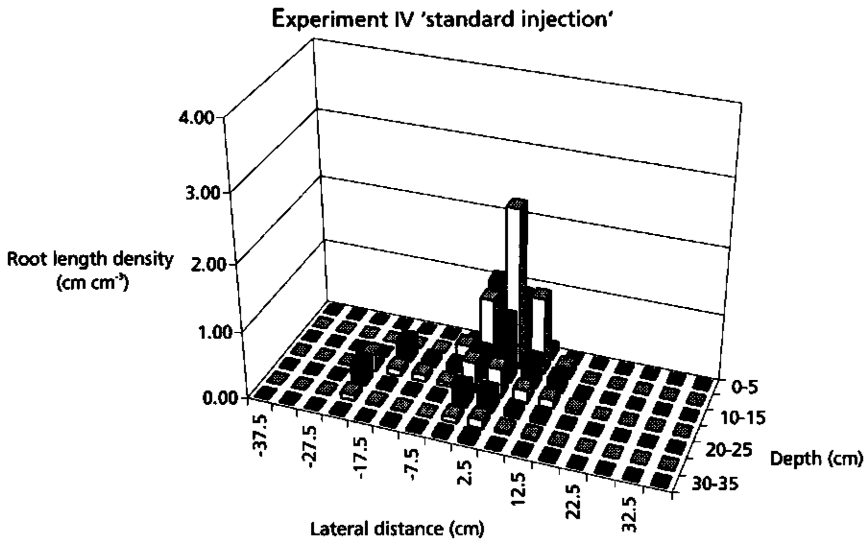
3.3.4 Weather conditions

Precipitation and average daily temperature during the growing season (May-October) were close to the long term average. However, during the first 8 weeks after emergence, maize crops suffered from drought in Experiments I and V and from cold stress in Experiments IV (Table 3.3).

Table 3.3. Precipitation (mm) and average daily temperature (°C) in Wageningen.

		Precipitation				Temperature			
Experiment		I	II/III	IV/V	long term average*	I	II/III	IV/V	long term average*
Month	May	89	50	82	61	14.3	14.1	12.5	12.3
	June	33	57	61	68	15.9	15.6	15.0	15.2
	July	184	165	33	75	16.1	16.0	20.8	16.8
	August	59	39	40	71	15.3	14.6	17.4	16.7
	September	153	132	137	67	13.1	12.9	13.7	14.0
	October	90	86	108	72	9.0	8.8	9.2	10.5

* 1961-1990 average at De Bilt



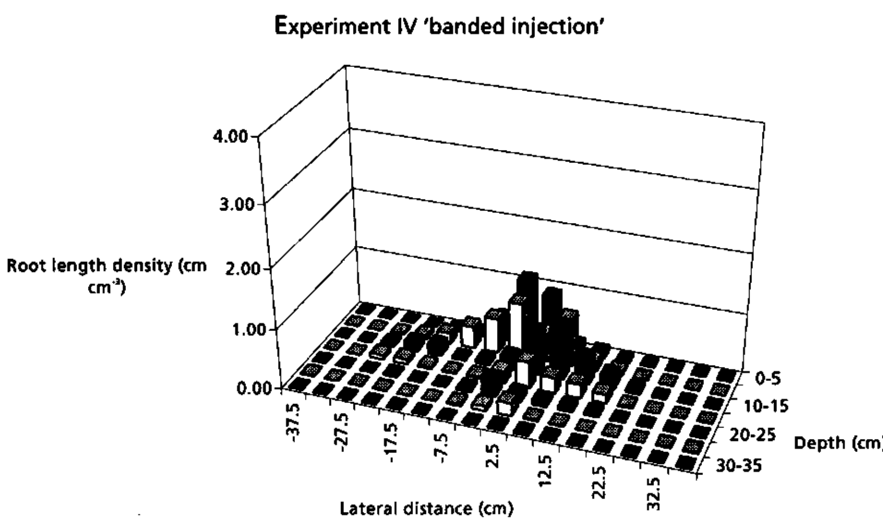
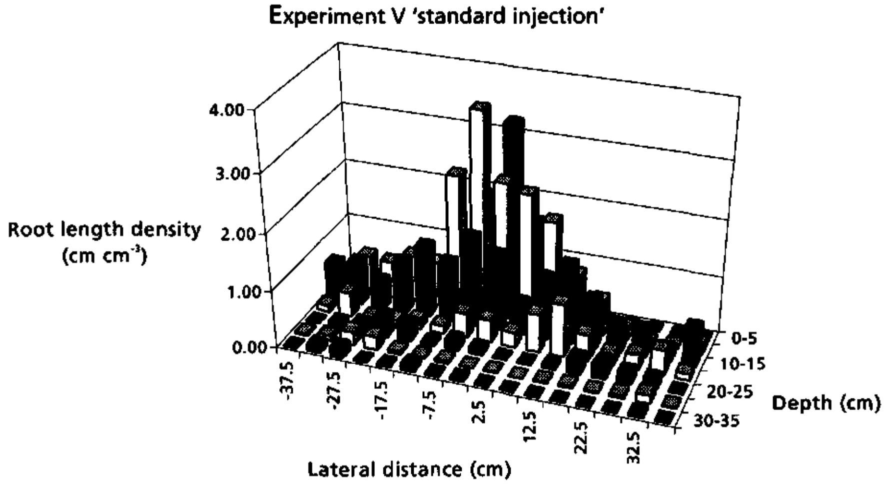


Figure 3.1a. Vertical and horizontal distribution of a maize root system (expressed as root length density) under maize 7 weeks after planting after conventionally injected slurry ('standard injection') and banded slurry ('banded injection') in Experiment IV (maize row positioned at 0 cm, standard injection positioned at 3 random positions between -37.5 cm and +37.5 cm, banded injection positioned at +10 cm).



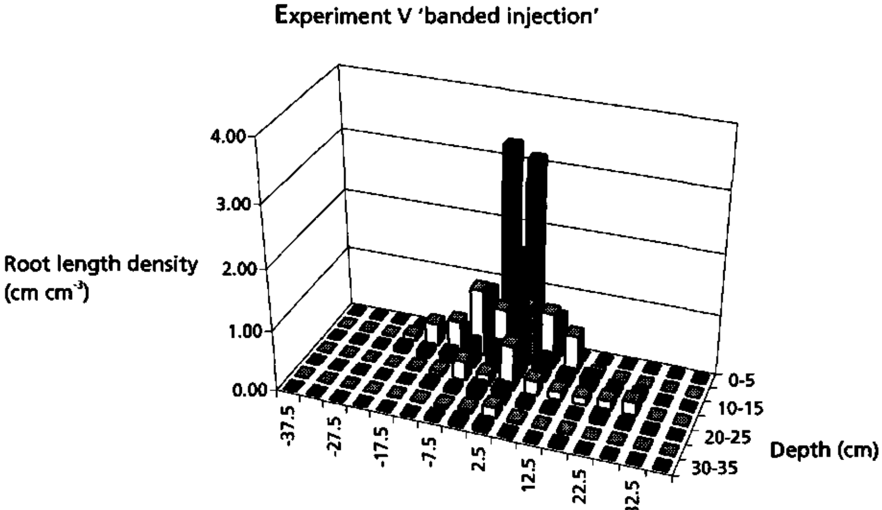


Figure 3.1b. Vertical and horizontal distribution of a maize root system (expressed as root length density) under maize 5 weeks after planting after conventionally injected slurry ('standard injection') and banded slurry ('banded injection') in Experiment V (maize row positioned at 0 cm, standard injection positioned at 3 random positions between -37.5 cm and +37.5 cm, banded injection positioned at +10 cm).

3.4 Results

Plant densities amounted to 10-11 plants m^{-2} without significant effects of the slurry application method (Table 3.4). Measurements of the root length density in Experiment IV showed that the extension of the roots had not yet passed a depth of 30 cm. The lateral extension was restricted to a 25 cm wide strip on both sides of the plant row. Root length densities were less than 1 cm cm^{-3} except for the soil volume directly underneath the seed (Figure 3.1a).

Similar measurements in Experiment V also showed marked horizontal and vertical gradients of the root length density. In most of the profile root length density was less than 1 cm cm^{-3}. The lateral root extension had progressed further when slurry had been conventionally injected ('standard injection') than when it had been banded ('banded injection') (Figure 3.1b).

During the first 10 weeks after planting, SMN was predominantly taken up from the soil compartments directly under the plant as indicated by measurements under and in between the maize rows. Horizontal gradients were stronger in fertilised treatments than in the corresponding controls, except for Experiment IV (Figure 3.2).

A significant positive response of the DM yield of silage maize to P-starter fertiliser was only observed in Experiments II and III. Such a response was not observed in Experiment I, despite a similar soil P content (Table 3.5). In all experiments, slurry placement increased the DM yields markedly when no P-starter fertiliser had been applied, as compared to the conventional slurry injection. The response to placement was strongest and significant on sites where crops were most responsive to P-starter fertiliser.

Table 3.4. Plant density (m^{-2}) as affected by the slurry application method.

Year	Experiment	Treatment			LSD
		control	standard	banded	(P<0.10)
1993	I	10.7	10.7	10.6	0.2
	II	10.8	10.7	10.8	0.4
	III	11.0	11.1	11.3	0.5
1994	IV	10.0	9.9	10.3	0.4
	V	10.0	10.1	9.9	0.3

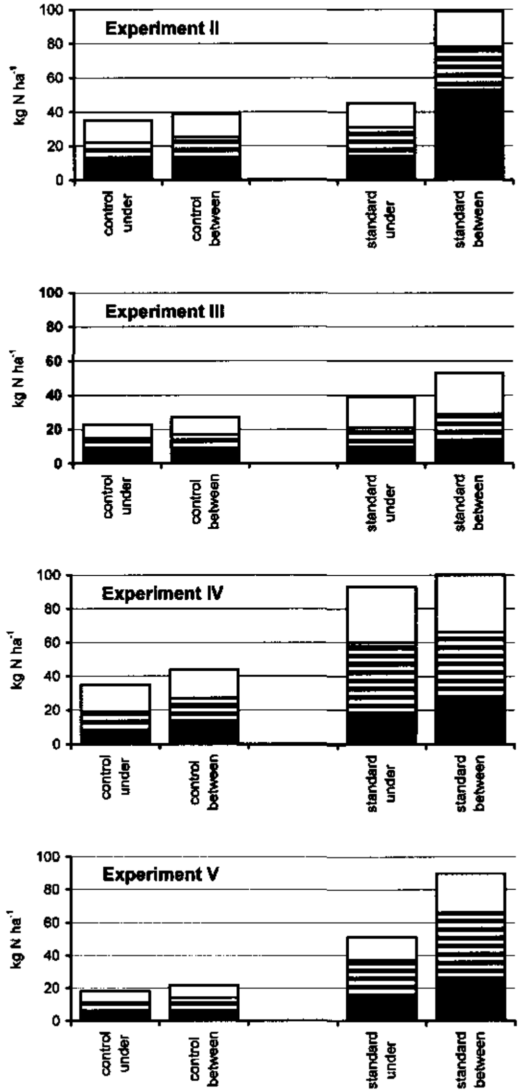


Figure 3.2. Vertical and horizontal distribution of soil mineral N under a maize crop about 10 weeks after planting in controls without slurry and after conventionally injected slurry ('standard injection') (under = under the plant row; between = in the middle between two plant rows; □ = 0-20 cm depth, ⊟ = 20-40 cm depth, ■ = 40-60 cm depth).

Table 3.5. DM yield of silage maize (t ha^{-1}) as affected by the slurry application method and rate and P-starter fertiliser.

Treatment			Experiment					Average	
slurry application method	rate (m^3 ha^{-1})	P-starter (kg ha^{-1})	I	II	III	IV	V	I-V	II-V
control	0	0	8.4	10.6	9.8	10.4	11.4	10.1	-
standard	30	0	11.4	11.8	10.8	12.6	12.7	11.9	-
banded	30	0	12.0	13.2	11.9	13.2	13.3	12.7	-
control	0	22	7.4	12.0	12.1	9.7	12.5	10.7	11.6
standard	30	22	11.2	13.7	12.7	13.0	14.4	13.0	13.4
banded	30	22	12.2	13.9	13.3	13.0	12.6	13.0	13.2
standard	60	22	-	15.5	12.9	15.3	13.2	-	14.2
banded	60	22	-	15.4	13.3	13.8	14.6	-	14.3
LSD ($P<0.05$)		1.7	0.9	0.8	1.6	1.7	0.7	0.7	

DM yields responded positively ($P<0.05$) to the application of 30 m^3 ha^{-1} slurry in all five experiments. Doubling the slurry rate to 60 m^3 ha^{-1}, however, only resulted in a significant further yield increase of the DM yield of the maize in Experiment II (Table 3.5).

P-starter fertiliser increased the apparent recovery of slurry-N on average by 7 percent and increased the N deficit by 7-9 kg ha^{-1} (Table 3.6). Refraining from P-starter fertiliser reduced the P-surplus considerably ($P<0.05$), be it at the expense of DM yield. Slurry placement compensated for this yield loss (Table 3.5). The N surplus and the apparent recovery of slurry N in treatments with banded slurry without a P-starter were similar to the conventionally injected slurry treatment combined with a P-starter.

Increases in the uptake of N from slurry due to placement were proportional to increases in the DM yield when no starter-P was used, as indicated by a significant increase of the apparent N efficiency and the absence of any response of the N content of the crop. In combination with a P-starter, the recovery of slurry-N was not significantly increased by placement and effects of placement on the DM yield and the ANE were not observed.

Table 3.6. P- and N surplus (kg ha^{-1}), apparent N recovery (ANR, kg kg^{-1}), apparent N efficiency (ANE, kg kg^{-1}) and N content of silage maize DM (kg kg^{-1}) as affected by the slurry application method and P-starter fertiliser (averaged over Experiments I-V).

Treatment			Surplus		ANR	ANE	N content
slurry application		P-starter	N	P			
method	rate (m^3 ha^{-1})	(kg ha^{-1})					
control	0	0	-110	-20	-	-	0.0109
standard	30	0	-23	-2	0.29	15	0.0122
banded	30	0	-30	-4	0.35	22	0.0122
control	0	22	-118	8	-	-	0.0110
standard	30	22	-32	24	0.36	24	0.0118
banded	30	22	-37	23	0.42	24	0.0124
LSD (P<0.05)		17	4	0.13		6	0.0009

3.5 Discussion

A poor synchronisation and synlocalisation of roots and nutrients can limit the actual availability of nutrients to crops (De Willigen & Van Noordwijk, 1987). Consequently, nutrient uptake and DM production may be reduced. Such a situation is most likely when the soil volume is not fully exploited by the root system due to plant or soil properties or row spacings. Farmers tend to respond to this by applying extra nutrients. This may ensure timely nutrient availability but will inevitably lead to larger nutrient surpluses and may eventually increase the losses to the environment.

Observations on the distribution of the root system in two of the five experiments confirm that the exploitation of the soil is far from complete during the juvenile stage of a maize crop. This is a direct result of the wide row spacing. Low temperatures may aggravate this through negative effects on the specific root length (Kiel & Stamp, 1992; Schröder *et al.*, 1995).

Root observations in Experiment V show that the lateral extension of the roots was less for banded slurry than for conventionally injected slurry. Such an interaction between the proliferation of roots and the presence of nutrients was also reported by Granato & Raper (1989), Shaviv & Hagin (1991) and Schröder *et al.* (1996a). In accordance with observations made by Schröder *et al.* (1996a), lateral extension occurred at depths of 10-20 cm rather than the upper 10 cm. This can explain why maize may respond weakly to N when applied in between the rows under dry conditions (Jokela & Randall, 1989; Bundy *et al.*, 1992).

Results from our experiments indicated that the benefits of fertiliser placement also hold for cattle slurry. The nutrient uptake and DM production of maize were increased by planting maize in rows next to equidistant slurry injection slots ('banded injection') as compared to maize planted in a soil where slurry had been injected more evenly ('standard injection'). Effects may result from a better N or a better P availability, as placement benefits are reported for N and P and slurry contains both. Effects in our experiments were strongest and significant on sites with a marked response to subsurface banded P-starters. Therefore, we conclude that slurry placement has mainly improved the availability of P. Significant positive effects of slurry placement were absent when P-starter had been used. In Experiment V maize yields even responded negatively ($P<0.05$) to slurry placement when combined with a P-starter.

The positive response to an increase of the slurry rate from 30 to 60 m^3 ha^{-1} apparently resulted from a demand for N rather than a demand for extra P, since slurry placement had no effect on maize DM yields when P-starter had been used. Contrary to the effect observed in the 30 m^3 ha^{-1} treatment, placement of 60 m^3 ha^{-1} in combination with P-starter had no negative effect on maize yield in Experiment V. Hence, salt damage is an unlikely explanation for the observed negative placement effect in the 30 m^3 ha^{-1} treatment.

In experiments where SMN was recorded we observed a marked lateral gradient, suggesting that N was predominantly taken up from zones in the soil with the largest root length density. Apparently, N was not instantaneously replenished from the neighbouring volume. Such persistent N gradients were reported earlier by Aufhammer *et al.* (1991), Lorenz (1992), Schröder *et al.* (1996a) and Clay *et al.* (1995) and may explain why maize also responded positively to placement on sites and in treatments where P-starter had no or only minor effects on maize DM yields. Such positive N placement effects are most likely to occur under dry conditions (De Willigen & Van Noordwijk, 1995) and may therefore explain the positive response to placement in Experiments I and V.

We did not observe a weaker response to P-starter or slurry placement when planting dates were postponed. This may be so because early and late planted maize grew up under similar temperatures in 1993 (Table 3.3). In 1994 when temperature during the juvenile stage of the early planted crop was considerably lower than it was in the late planted crop, P-starter did not significantly affect the DM yield of the early planted maize. Probably, P-starters were ineffective on that site due to a higher initial soil P status and the overall dressing of 45 kg P ha^{-1} applied to all treatments.
A better availability of P appeared to have a positive effect on the apparent recovery of slurry-N (Table 3.6). Such an effect was reported earlier by Schlegel & Havlin (1995). Slurry placement increased the apparent recovery of slurry N up to a value that was obtained with conventionally injected slurry in combination with a P-starter. Recoveries were 6 percent larger with banding than with the conventionally injected slurry. This increase was not significant at the 95% probability level but trends were the same both with and without P-starter. Such an increase of the recovery is less than what one can calculate from the mathematical description of the placement effects of mineral fertilisers proposed by De Wit (1953). According to his formula, recovery would have been about 20 percent larger (absolute) when slurry is banded in 15-20 cm wide strips than when the same amount of slurry is homogeneously distributed through a soil volume of similar depth. Possibly, our conventionally injected slurry was less evenly distributed than we assumed and banded slurry may have been redistributed in the soil over a larger width. Moreover, banding may have created spots with a greater risk for denitrification (Rice *et al.*, 1988).
In conclusion, slurry placement can minimise the risk of yield loss associated with reduced fertiliser inputs and contribute to a better balance of fertiliser inputs and crop nutrient offtakes. Therefore, slurry placement can be a useful tool in any farming system that tries to or is forced to improve its fertiliser use efficiency.

CHAPTER 4

EFFECTS OF NITRIFICATION INHIBITORS AND TIME AND RATE OF SLURRY AND FERTILISER N APPLICATION ON SILAGE MAIZE YIELD AND LOSSES TO THE ENVIRONMENT

J.J. Schröder, L. ten Holte, H. van Keulen and J.H.A.M. Steenvoorden

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4.1 Abstract

Field experiments with silage maize on a sandy soil in The Netherlands showed that dicyandiamide (DCD) addition to autumn-applied cattle slurry retarded nitrification, thus reducing nitrate losses during winter. Spring-applied slurry without DCD, however, was on average associated with even lower losses and higher maize dry matter yields.

Economically optimum supplies of mineral N in the upper 0.6 m soil layer in spring (EOSMN), amounted to 130-220 kg ha^{-1}. Year to year variation of EOSMN could not be attributed to crop demand only. According to balance sheet calculations on control plots, apparent N mineralisation between years varied from 0.36 to 0.94 kg ha^{-1} d^{-1}. On average, forty percent of the soil mineral N (SMN) supply in spring, was lost during the growing season. Hence, the amounts of residual soil mineral N (RSMN) were lower than expected. Multiple regression with SMN in spring, N crop uptake and cumulative rainfall as explanatory variables, could account for 79 percent of the variation in RSMN.

Postponement of slurry applications to spring and limiting N inputs to economically optimum rates, were insufficient measures to keep the nitrate concentration in groundwater below the EC level for drinking water.

Keywords: maize, animal manure, nitrogen recovery, nitrification inhibitor, leaching

4.2 Introduction

Animal manure is frequently spread in autumn because storage capacity for manure is insufficient to allow postponement till the next spring. Moreover, spring application may damage soil structure, especially on heavier soils. The long residence time of autumn-spread manure may result in more nitrogen (N) being lost through runoff, volatilisation, leaching and denitrification.
Ammonia N present in, or mineralised from manure, can rapidly be nitrified. This process continues during winter in Northwestern Europe (Vilsmeier & Amberger, 1987). In mild and wet winters, nitrate may be lost through denitrification or leaching. Apart from financial considerations, N losses also deserve attention from an environmental point of view. Nitrous oxide resulting from denitrification has a detrimental effect on the ozone layer and contributes to the greenhouse effect (Bach, 1989) and N leaching may eventually lead to nitrate concentrations in groundwater exceeding 11.3 mg nitrate-N l^{-1}, the European Community (EC) standard for drinking water (Anonymous, 1980).
In cereal dominated rotations, N losses from manure can be restricted by immobilisation with straw or N storage in cover crops. However, in regions with high livestock densities, cereals have been substituted by continuous silage maize, partly because of its tolerance for excessive manure applications (Schröder & Dilz, 1987). Therefore maize cropping is associated with great risks for N losses in these regions. Crop characteristics augment the risks even more; the quantity and quality of maize residues restrict microbial immobilisation of soil mineral nitrogen (SMN) and its late harvest does not always allow timely establishment of a cover crop (Schröder *et al.*, 1992a). Moreover, the roots of the subsequent maize crop will not explore deeper soil layers until June, thus limiting interception of leached nitrogen. Where incorporation of straw or growth of cover crops is not feasible, denitrification and leaching may be reduced by the use of nitrification inhibitors which delay the transformation of ammonium into nitrate. Dicyandiamide (DCD) and 2-chloro-6-(trichloromethyl)pyrimidine (N-Serve) have demonstrated their usefulness in this respect (Hauck, 1980). DCD effectiveness may be low, however, when its decomposition is stimulated by high temperatures (Solansky, 1981).

Between 1981 and 1989 we conducted field experiments to investigate the effect of time and rate of fertiliser and slurry application, and nitrification inhibitors on soil mineral N, leaching and N availability for maize.

4.3 Materials and methods

4.3.1 Setup and treatments

Experiments were executed between autumn 1981 and autumn 1989 in Wageningen, The Netherlands (52° N, 6° E), on a sandy soil with 34 g of organic matter, 50 g of silt, 18 mg of water soluble P, 83 mg exchangeable K per kg soil and a pH-KCl of 5.5 in the top 0.2 m. Depth of the groundwater table varied between 0.7 and 1.0 m for most of the time. The trials were located at different sites except for the growing seasons of 1986-1989 when treatments returned to exactly the same plot each year.
Between 1982 and 1985 combinations of autumn-applied cattle slurry (either with or without DCD) and spring-applied mineral fertiliser N (calcium ammonium nitrate, CAN) were investigated. Cattle slurry rates included a control and will be discussed later. Mineral fertiliser rates were 0, 50 (not in 1982), 100 and 200 kg N ha^{-1}. In 1984 and 1985 the experiment was extended to include spring-applied cattle slurry treatments with or without DCD. From 1986 till 1989 a comparison was made between the effect of 160 kg mineral fertiliser N (calcium nitrate, CN) and approximately 250 and 500 (130 and 260 in 1986) kg total N ha^{-1} from cattle slurry, applied either without nitrification inhibitor, with DCD or with N-Serve. Slurry was applied in either the second half of October (late summer), the end of November (autumn) or in March (spring). The experiments were set up as a split plot or strip plot trial with 3 (4 in 1982) replicates. Main plots (strips) consisted of cattle slurry rates with or without DCD in 1982, N rates in 1983-1985 and application times in 1986-1989. Subplot size varied between 45 and 90 m^2.
Silage maize (*Zea mays* cv. LG11 in 1982 and Splenda in 1983-1989) was planted around May 1st at a density of 110.000 plants ha^{-1} and harvested each year in October. Weeds were controlled chemically with atrazine-containing compounds. All plots received equal amounts of P, K and Ca mineral fertiliser to maintain soil fertility for these elements at recommended levels (Anonymous, 1989).

Cattle slurry was injected at a depth of 0.15 m (tine distance of 0.5 m) with a precision injector especially developed for field trials. The slurry was analysed for dry matter, total N, NH_4-N, P and K at each application date. Total N concentrations varied, mainly among experiments, between 3.0 and 5.6 g per kg fresh matter. Averaged over experiments concentrations amounted to 78 g dry matter, 4.3 g total N, 2.0 g NH_4-N, 0.7 g P and 4.5 g K per kg fresh matter. Changes in the experimental setup also caused the total N input from slurry to vary in the course of the years (Table 4.1). Until autumn 1984 DCD was applied at rates of 30 kg ha^{-1}, from 1985 at rates of 25 kg for late summer and autumn applications and 15 kg ha^{-1} (20 kg in 1985) for spring applications. The N concentration of DCD was 0.67 kg per kg. N-Serve (0.216 kg active ingredient per liter xylene) was applied at a rate of 3 l ha^{-1}. DCD and N-Serve were thoroughly mixed with the slurry before spreading.

4.3.2 Observations

Each year initial SMN and residual SMN (RSMN) supplies were assessed in spring (March-April) and autumn (October-November), respectively, before fertiliser application. From 1982 till 1987 SMN supply was also determined in late spring (June). SMN is defined as the sum of NO_3-N and NH_4-N. Between 1981 and 1985 sampling was restricted to subplots receiving no mineral fertiliser N except for the autumn samplings. Per subplot eight core samples were taken to a total depth of 0.6 m. Dry matter (DM) yield of the maize was determined by weighing the fresh material from a net area of 21 m^2 per subplot, DM content by drying a subsample of 0.8 kg at 105°C for 16 h. Dried samples were analysed for total N.

Nitrate leaching was assessed during the winters of 1985-1986, 1986-1987 and 1987-1988 in all subplots of the second replicate where no CN was applied in late summer or autumn. Leaching was assumed to start after the soil had been recharged to field capacity and calculated as the integral of the product of concentration and precipitation surplus over time. Nitrate concentrations were determined regularly in samples of the soil solution collected from four ceramic cups installed at 0.9 m depth. Precipitation

Table 4.1. Annual N applications (total N, kg ha^{-1}) in cattle slurry from autumn 1981 till spring 1989.

Year	Exp. site	application time	Approximate rate (kg N ha^{-1} yr^{-1}): 85	145	255	465
1981	a	autumn		165	335*	
1982	b	autumn		143	283*	570
1983	c	autumn	83	145	228*	
1984	c	spring	76	153	237*	
	d	autumn			312*	439
1985	d	spring		133	255*	368
	e	late summer		132	239	
	e	autumn	89		178*	
1986	e	spring			180*	354
	e	late summer			253	507
	e	autumn			279*	552
1987	e	spring			245*	490
	e	late summer			207	438
	e	autumn			225*	443
1988	e	spring			248*	487
	e	late summer			247	474
	e	autumn			247*	505
1989	e	spring			276*	553

* treatments used for the preparation of Figure 4.2 and Table 4.2.

surplus was estimated as the difference between precipitation and evapotranspiration (ET) taking account of the water storage capacity of the soil. ET was set equal to 0.3 * potential evapotranspiration (Penman) as calculated from data collected at a meteorological station 3 km from the experimental site.

4.3.3 Definitions

The relative increase in SMN supply due to slurry application is defined as: (SMN in spring on fertilised plots - SMN on non-fertilised plots) / (total N input with slurry and DCD).
Apparent mineralisation during summer, inclusive losses, was derived from the difference between total mineral N inputs and N outputs per treatment: (N yield of the harvested maize + RSMN) - (SMN in spring + mineral fertiliser N + ammonia-N in spring-applied cattle slurry + N from DCD). For the winter period apparent mineralisation, inclusive all non-leaching losses, equals: (SMN in spring + leached mineral N) - (RSMN in preceding autumn + ammonia-N in late summer- or autum-applied cattle slurry + N from DCD).
The economically optimum SMN supply (EOSMN) was estimated by setting the first derivate of the relationship between SMN supply in spring and silage maize DM yields, obtained from quadratic regression analysis, equal to a price ratio of silage maize and N of 7. SMN supply is defined as the sum of SMN in spring (0-0.6 m), NH_4-N in spring-applied slurry and mineral fertiliser N. Values exceeding 300 kg N ha^{-1} were excluded from the regression analysis.
Apparent N recovery (ANR) of fertiliser N was defined as the difference in N yield between a fertilised and a non-fertilised crop expressed as a percentage of the N rate (N from DCD included), ANR of SMN as the difference in N yield between a fertilised crop and the estimated N uptake at zero SMN expressed as a percentage of the SMN supply. Strictly speaking, non-fertilised crops were absent between 1986 and 1989, hence subplots that received CN in the preceding late summer were used as a reference. This seems justified as only 22-44 kg SMN ha^{-1} (0-0.6 m) was found in these plots in spring, even less than the 26-55 kg ha^{-1} on non-fertilised plots during the 1982-1985 period. Apparently, the 160 kg N ha^{-1} from CN was completely lost from the surface 0.6 m during winter.

4.3.4 Weather conditions

For the experimental period precipitation between October and March was close to average (374 mm) except for 1984-1985 (312 mm) and 1987-1988 (517 mm). Precipitation between April and September was more or less average (388 mm), except for 1982 (287 mm), 1985 (448 mm), 1986 (303 mm) and 1987 (462 mm). Average daily temperature between October and March was close to normal (4.8°C) except for 1985-1986 (3.4°C), 1987-1988 (6.0°C) and 1988-1989 (6.7°C). Average daily temperature between April and September was close to normal (13.8°C) except for 1984 (12.8°C).

4.4 Results

4.4.1 Nitrification inhibitors and application time

DCD augmented the relative increase of the SMN supply derived from late summer- and autumn-applied slurry from 20 to 35 percent on average; however, the values varied considerably among years. This variation was not related to the heat sum during the first 6 weeks after DCD application (Figure 4.1). DCD-addition to autumn-applied slurry reduced nitrification and the subsequent transport of N to deeper layers (Figure 4.2), and increased the N yield of maize in all years except 1984 and DM yields in all years except 1984 and 1985; averaged over the years, ANR of autumn-applied slurry increased from 21 to 26 percent (Table 4.2).

Soil sampling in June during the 1984-1987 period showed that SMN supply in June was similar on plots where slurry had been applied in autumn with DCD and in spring with or without DCD. Nevertheless, N yields and DM yields of maize were higher in 4 out of 6 and 3 out of 6 years, respectively, with spring-applied slurry without DCD than with DCD-treated autumn-applied slurry . The effect of spring-applied slurry on N yields and DM yields of maize was further improved by addition of DCD in 5 out of 6 and 3 out of 6 years, respectively. Averaged over the 1984-1989 period, ANR of autumn-applied slurry without, autumn-applied slurry with, spring-applied slurry without and spring-applied slurry with DCD was 20, 27, 29 and 33 percent, respectively. N-Serve addition to autumn-applied slurry had less effect than DCD on SMN supply in spring and N and DM yields of maize (Table 4.2).

4.4.2 N availability during the growing season

EOSMN supplies in spring ranged from 130 to 220 kg N ha^{-1} (Table 4.3). In seven out of eight years N yields could be described significantly by a quadratic function of the SMN supply in spring. ANR of SMN at optimum

SMN supply varied between 30 and 82 percent; the ANR was higher at suboptimum levels of SMN supply. At half the optimum SMN supply, yield was depressed between 5 and 17 percent (Table 4.4).

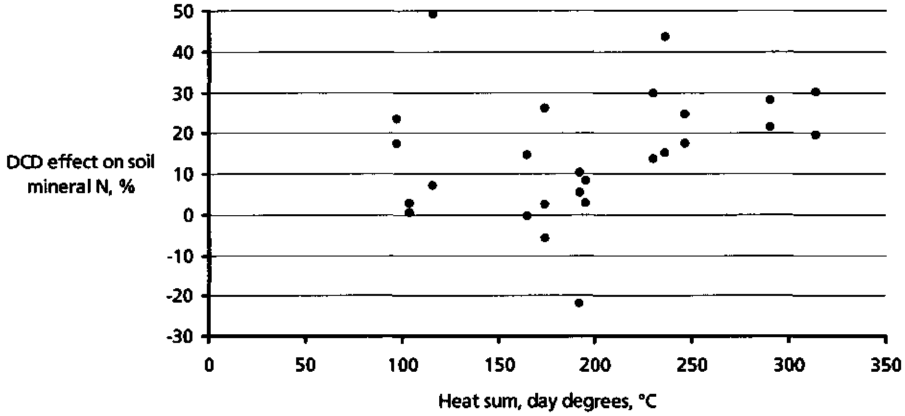


Figure 4.1. Change due to DCD in the relative increase in soil mineral N supply in spring (upper 0.6 m soil layer, expressed in percent of total N input) resulting from slurry applied in late summer or autumn, as affected by the heat sum (>0°C) during the first six weeks after spreading (1982-1989).

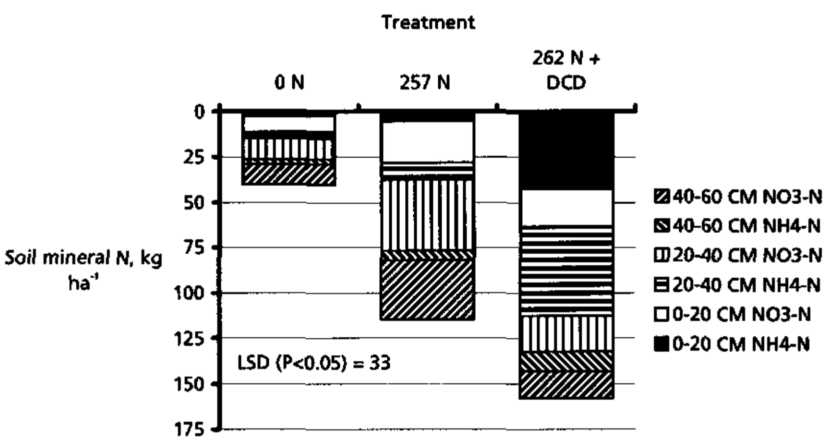


Figure 4.2. Effects of DCD addition to late summer- and autumn-applied cattle slurry on the amounts of nitrate and ammonia in the upper 0.6 m soil layer in spring (average 1982-1989).

Table 4.2. Dry matter and N yield of silage maize and apparent recovery of total N from cattle slurry as affected by application time and nitrification inhibitor addition.

Exp. period	Application time	Nitrification inhibitor	Total N input ($kg\ ha^{-1}\ yr^{-1}$): with slurry	with inhibitor	DM yield ($t\ ha^{-1}\ yr^{-1}$)	N yield ($kg\ ha^{-1} yr^{-1}$)	ANR (%)
1982-89	autumn	-	0	0	11.5	117	-
		-	257	0	14.8	170	21
		DCD	262	18	15.6	191	26
			(LSD, P<0.05)		0.4	7	
1984-89	autumn	-	0	0	10.8	111	-
		-	239	0	14.3	159	20
		DCD	247	18	15.1	182	27
	spring	-	249	0	15.4	184	29
		DCD	249	12	15.7	198	33
			(LSD, P<0.05)		0.5	8	
1986-89	autumn	-	0	0	10.5	100	-
		-	227	0	14.0	144	19
		DCD	232	17	15.5	178	31
		N-Serve	238	0	14.5	155	23
	spring	-	237	0	15.7	177	32
		DCD	237	10	15.7	184	34
		N-Serve	237	0	15.3	177	32
			(LSD, P<0.05)		1.0	17	

Apparent mineralisation between March and October on plots without N fertiliser amounted to 110 kg N ha^{-1} yr^{-1} on average (range 68-162), equivalent to 0.54 (range 0.36-0.94) kg ha^{-1} d^{-1}. Lowest values were found in years with low temperatures (1984) and high precipitation (1987).
On fertilised plots the calculated apparent mineralisation was generally lower, suggesting that N losses during the growing period were related to SMN supplies. Linear regression analysis of the initial SMN supply in spring and the sum of N yield of maize and RSMN suggested that apparent mineralisation would have been 138 kg N ha^{-1} yr^{-1} at a hypothetical initial SMN supply of zero (Figure 4.3).

Table 4.3. Calculated constants of the equation $DMY=a+(0.01*b)SMN-(0.00001*c)SMN^2$ (derived from regression analysis) between DM yield (DMY, t ha^{-1}) and SMN supply in the upper 0.6 m soil layer in spring (kg ha^{-1}), the variance accounted for (VAF, %), the economically optimum SMN supply (EOSMN, kg ha^{-1}) and the calculated (see Table 4.4) N yield at this EOSMN (NYOP, kg ha^{-1}).

Exp. year	Value/ significance [1]	Constants: a	b	c	VAF	EOSMN	NYOP
1982	value	9.42	5.255	10.44	92	218	196
	sign.	***	***	***			
1983	value	12.55	4.02	7.91	65	210	217
	sign.	***	***	***			
1984	value	8.43	3.321	8.39	45	156	169
	sign.	***	***	***			
1985	value	13.67	4.01	8.61	15	192	256
	sign.	***	**	*			
1986	value	13.48	4.57	15.06	25	128	182
	sign.	***	**	**			
1987	value	8.97	2.42	4.26	32	202	144
	sign.	***	NS	NS			
1988	value	10.75	5.54	12.53	64	193	219
	sign.	***	***	***			
1989	value	7.47	9.51	20.58	88	214	221
	sign.	***	***	***			

1 NS not significant, * P<0.10, ** P<0.05, *** P<0.01

Table 4.4. Calculated constants of the equation $NY=a+(0.01*b)SMN-(0.00001*c)SMN^2$ (derived from regression analysis) between N yield (NY, kg ha^{-1}) and SMN supply in the upper 0.6 m soil layer in spring (kg ha^{-1}), the variance accounted for (VAF, %), apparent N recovery of SMN (ANR, %) at economically optimum SMN supply (EOSMN, see Table 4.3) and at half the EOSMN and calculated (see Table 4.3) relative DM yield (RY, in % of DM yield at EOSMN) at half the EOSMN.

Exp. year	Value/ significance [1]	Constants: a	b	c	VAF	SMN supply: EOSMN: ANR	0.5*EOSMN: ANR	RY
1982	value	73.4	78.4	100.8	94	56	90	87
	sign.	***	***	***				
1983	value	151.4	36.4	25.4	66	31	34	91
	sign.	***	***	NS				
1984	value	96.1	66.8	130.0	70	47	57	95
	sign.	***	***	***				
1985	value	172.4	57.3	72.5	37	43	50	92
	sign.	***	***	*				
1986	value	138.1	42.5	63.0	39	34	38	90
	sign.	***	NS	NS				
1987	value	82.9	43.7	67.3	52	30	37	91
	sign.	***	**	*				
1988	value	103.3	91.8	166.0	78	60	76	89
	sign.	***	***	**				
1989	value	46.2	121.8	188.5	88	81	102	83
	sign.	***	***	***				

1 NS not significant, * P<0.10, ** P<0.05, *** P<0.01

The sum of N yield and RSMN, however, was always substantially lower than the sum of SMN supply in spring and the estimated mineralisation of 138 kg N ha^{-1}. In general, about 40 percent of the SMN supply could not be accounted for in either N yield or RSMN. As SMN supplies increased from 50 to 200 kg ha^{-1}, ANR of SMN by the crop decreased from 47 to 39 percent and RSMN increased from 32 to 54 kg ha^{-1}.

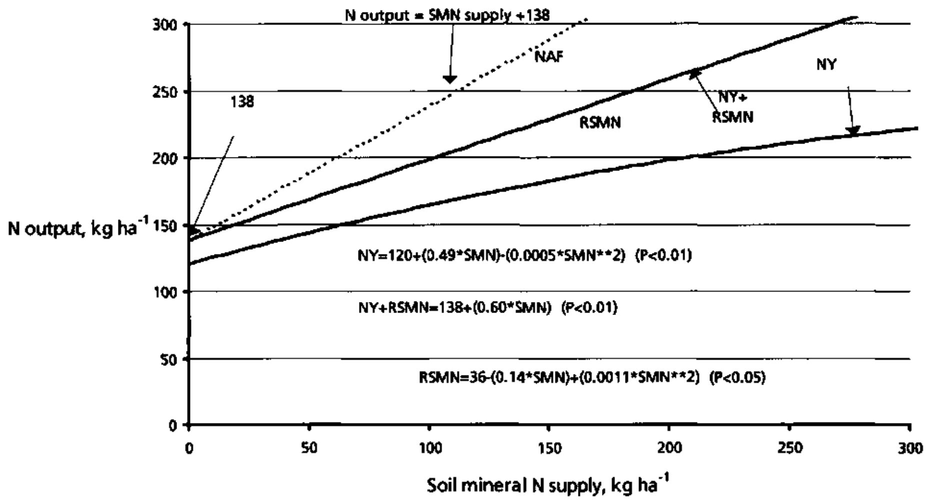


Figure 4.3. Allocation of soil mineral N (SMN) in spring (upper 0.6 m soil layer) to uptake in the aerial plant parts of maize (NY), residual soil mineral N (RSMN, upper 0.6 m soil layer) and losses not accounted for (NAF); (average 1982-1989).

4.4.3 Residual N and subsequent losses

RSMN was strongly influenced by the SMN supply in spring but the relation varied from year to year (Figure 4.4). Relatively large quantities were found following dry seasons (1982, 1983, 1989), whereas only moderate amounts were observed after wet summers (1984, 1987), despite low N yields in those years. Variance accounted for (VAF) increased from 60 to 79 percent if the linear regression model relating RSMN to SMN supplies was extended to include cumulative rainfall between May 1st and the date of post harvest soil sampling and N yield (Table 4.5). According to this model any increase in rainfall or in N yield up to 50-100 kg ha^{-1}, reduced RSMN. Predictability of RSMN was not improved by including temperature as a variable.

Measurements on the fate of N during winter showed SMN in spring to be lower than the sum of RSMN and mineral N from slurry applied in the preceding late summer or autumn (Figure 4.5). With only few exceptions this also occurred in plots where DCD had been added. These apparent losses are partly the result of N leaching. In the first two winters when leaching was monitored, only half the leaching (both in terms of water volume and N) actually took place in winter, the remainder occurring between March and June (data not shown). Generally, nitrate concentrations (weighted average over the complete leaching period) were higher and more responsive to rates for late summer- and for autumn-applied slurry than for spring-applied slurry. DCD restricted nitrate leaching only slightly under late summer or autumn-applied slurry; when added to spring-applied slurry it even resulted in higher nitrate concentrations in subsequent winters (Figure 4.6A-C). Ammonia leaching was restricted to 1-2 kg N ha^{-1} yr^{-1} in both DCD- and non-DCD-treated plots.

Balance sheet calculations for the winter period indicated net gains in SMN in the mildest of the three winters. Averaged over years the net change in SMN (excluding leaching losses) was inversely related to slurry rate (Table 4.6).

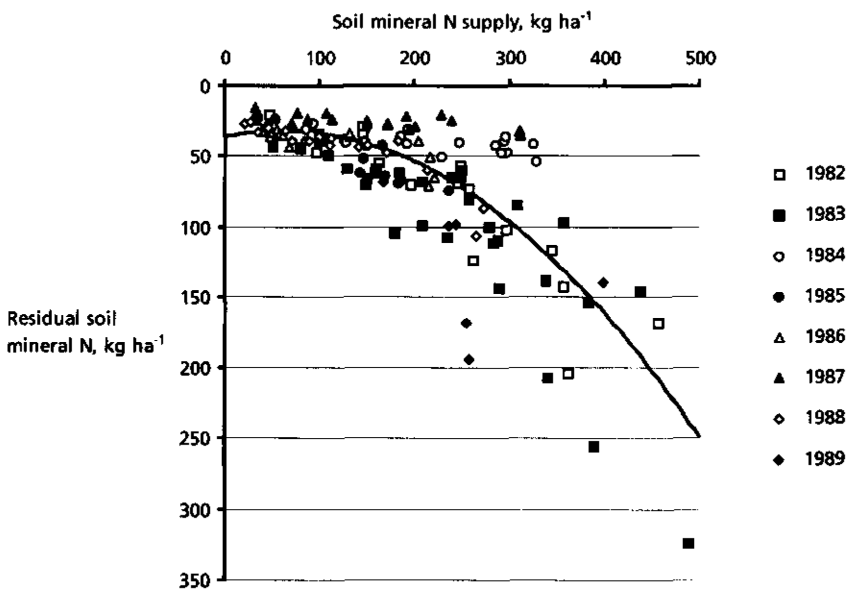


Figure 4.4. Residual soil mineral N (upper 0.6 soil layer) after the harvest of silage maize as affected by the SMN supply in spring (upper 0.6 soil layer).

Table 4.5. Linear regression models relating the amount of residual soil mineral N in the upper 0.6 m soil layer in autumn (RSMN, kg ha^{-1}) to the soil mineral N supply in the upper 0.6 m soil layer in spring (SMN, kg ha^{-1}), cumulative precipitation between May 1st and autumn soil sampling date (RAIN, mm) and N yield of maize (NY, kg ha^{-1}): $RSMN = a + b*SMN + c*SMN^2 + d*RAIN + e*RAIN^2 + f*NY + g*NY^2$.

Constant:	Value/ significance [1]	Terms of the model: SMN	SMN, RAIN	SMN, RAIN, NY
a	value	36.1	-92.3	110.0
	sign.	***	**	***
b	value	-0.138	-0.0865	-0.2269
	sign.	*	*	***
c	value	0.001126	0.000995	0.001029
	sign.	***	***	***
d	value		0.919	
	sign.		***	
e	value		-0.001507	-0.0001510
	sign.		***	***
f	value			-0.868
	sign.			***
g	value			0.003511
	sign.			***
Variance accounted for (%)		60	72	79

1 NS not significant, * P<0.05, ** P<0.01, *** P<0.005

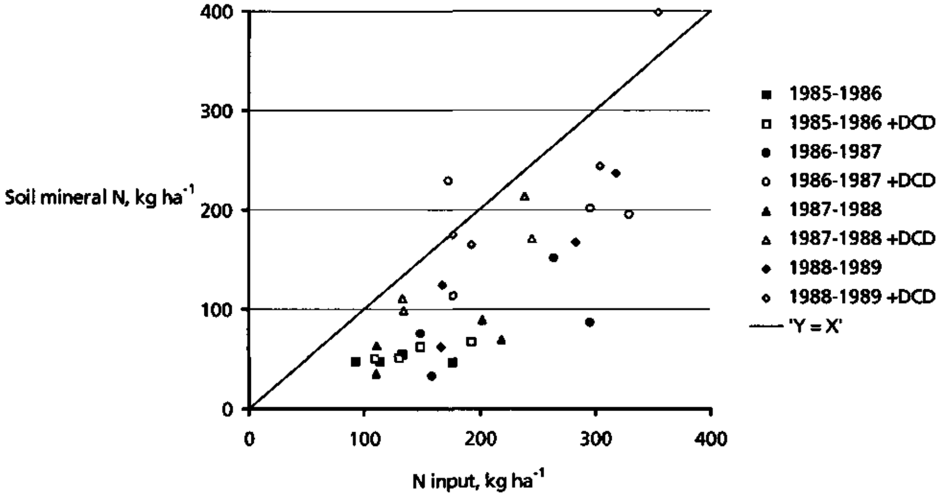


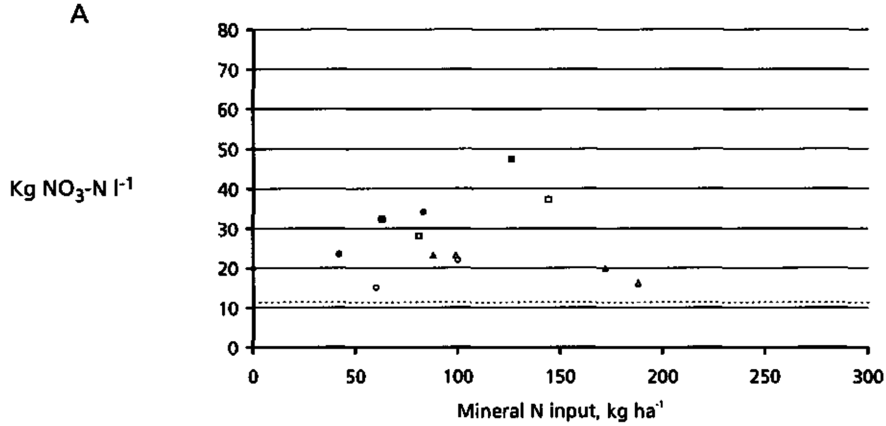
Figure 4.5. Soil mineral N in spring (upper 0.6 m soil layer) as affected by the N input from residual soil mineral N left by the preceding maize crop (upper 0.6 soil layer), H_4-N from late summer- or autumn-applied cattle slurry and N from DCD.

Table 4.6. Net change in mineral N supply in the upper 0.6 m soil layer (kg ha^{-1}) during winter excluding leaching losses

Application	Total N input (kg ha^{-1} yr^{-1}):		Year:		
time	with slurry	with DCD	1985-86	1986-87	1987-88
Late summer	191	0	-20	-38	23
	191	17	-31	-32	24
	392	0	-62	-62	-7
	399	17	-67	-56	50
Autumn	192	0	-13	-23	23
	199	17	-30	85	42
	378	0	-29	-14	1
	397	17	-48	-55	111

1985-1986

A



1986-1987

B

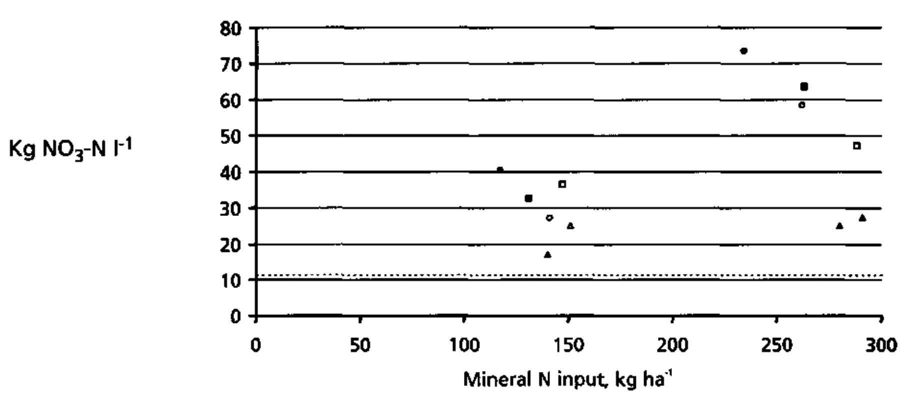


Figure 4.6 A-B Nitrate concentrations (weighted average over complete leaching period) at 0.9 m below soil surface as affected by time and rate of cattle slurry application and addition of DCD. (■ late summer, □ late summer + DCD, ● autumn, O autumn plus DCD, ▲ spring, Δ spring + DCD, ---- EC nitrate target concentration) in the winters of 1985-1986 (precipitation surplus 346 mm) and 1986-1987 (precipitation surplus 514 mm).

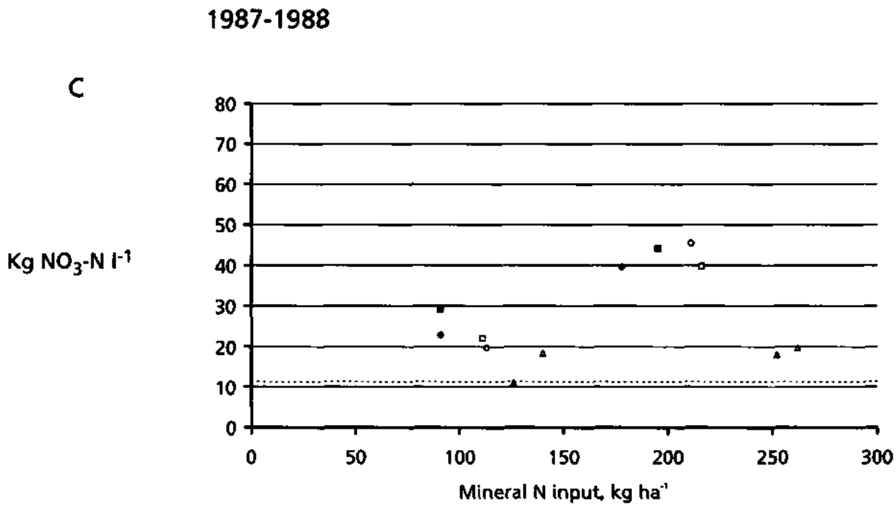


Figure 4.6C. Nitrate concentrations (weighted average over complete leaching period) at 0.9 m below soil surface as affected by time and rate of cattle slurry application and addition of DCD. (■ late summer, □ late summer + DCD, ● autumn, O autumn plus DCD, ▲ spring, Δ spring + DCD, ---- EC nitrate target concentration) in the winter of 1987-1988 (precipitation surplus 412 mm).

4.5 Discussion

Results of field experiments with silage maize on a sandy soil between 1981 and 1989 revealed strong relationships between DM yield, N yield and SMN supply in spring; SMN was a function of both fertiliser rate and application time. Apparently, risks for losses are related to the residence time of a fertiliser in the soil system. Leaching and denitrification are the major loss processes (Addiscott & Powlson, 1992). Our results indicate that DCD addition to late summer- or autumn-applied cattle slurry delayed nitrification and hence reduced subsequent losses of nitrate to a certain extent. However, DCD effects on the SMN supply varied greatly among years. We could not relate this variation to differences in cumulative temperatures after application although such a relationship between the decomposition rate of DCD and temperature has been reported (Solansky, 1981). In all years but 1984 and 1985, DCD addition to late summer- or autumn-applied slurry had a positive effect on maize DM yields as reported earlier (Amberger, 1986). However, DM yields in the present experiment were generally higher following application of similar amounts of slurry without DCD in spring. DCD addition to spring-applied slurry resulted in increased maize DM yields only in 1984, 1985 and 1987. 1984 was exceptionally cold, whereas 1985 and 1987 were much wetter than average. Low temperatures retarded crop development and N uptake in 1984 and may have reduced root extension during the juvenile stage (Tardieu & Pellerin, 1991). Abundant precipitation in 1985 may have promoted downward transport in early spring as it did in 1987, when monitored in our experiment. Under these circumstances DCD may have improved the 'synlocalisation' (De Willigen & Van Noordwijk, 1987) between SMN and active maize roots. The addition of N-Serve to autumn-applied slurry had a much smaller positive effect on SMN in spring than DCD. Consequently, N and DM yields of silage maize were intermediate between those from the control and DCD-treated plots.

ANR from cattle slurry by maize in this experiment was similar to that observed in many other studies (e.g. Schröder & Dilz, 1987; Schröder, 1990b; Schröder *et al.,* 1992a). As reported earlier (Van Dijk, 1985; Görlitz, 1989) recovery was improved by postponement of the application to spring.

EOSMN supply in spring, as defined in this paper, varied between 130 and 220 kg ha^{-1} . This variation could not simply be attributed to crop demand for N as both high and low optima may coincide with a low and a high N yield. The relation between the N uptake and the N applied may also depend on such factors as the magnitude of losses and N mineralisation during the growing season, rooting pattern and root functioning. In six out of eight years optimum SMN supply varied between 190 and 220 kg N ha^{-1}. This is in close agreement with the results of others (Bassel *et al.,* 1987; Beauchamp *et al.,* 1989; Blackmer *et al.,* 1989). SMN supply as we defined it, did not include the mineralisable N from cattle slurry. EOSMN supplies, as calculated here, may therefore be lower than in cropping systems where only mineral fertiliser N is used. This possible underestimate of the contribution of manure N is counteracted, however, by increased losses associated with manure such as ammonia volatilisation and denitrification. We did not account for these losses, although balance sheet calculations suggest that major losses occurred.

According to balance sheet calculations for the growing season, apparent mineralisation on non-fertilised plots varied on average between 0.36 and 0.94 kg N ha^{-1} d^{-1}. Apparent absolute losses increased with increasing N input. On average they amounted to 40 percent of the SMN supply in spring. As N storage in the root system can only account for about 25 kg ha^{-1} (Thom & Watkin, 1978), high summer losses must have other causes. At least in 1986 and 1987 losses could be attributed to leaching after crop emergence. Losses under young maize crops were also reported in (Wantulla *et al.,* 1988). Moreover, the greater availability of easily decomposable organic matter from animal manure may have stimulated losses through denitrification (Guenzi *et al.,* 1978; Maddux *et al.,* 1991). Although we injected the slurry, ammonia volatilisation losses from the injection slots cannot be completely discounted (Schröder, 1990b). However, substantial summer losses also occurred on plots where only mineral fertiliser N had been applied, in agreement with data from Jokela & Randall (1989) showing losses in the order of 30 percent. Greenwood *et al.* (1992), reported similar findings with onion crops.

At half the economically optimum SMN supply, yields were never depressed more than 17 percent. Prolonged suboptimal fertilisation, however, may lead to larger yield reductions as suggested by results from the continuous experiment between 1986 and 1989 and by other evidence (e.g. Motavalli *et al.,* 1992).

As a result of losses during the growing season, RSMN was lower than expected from the difference between SMN supply and N yield, especially in wet years. In agreement with Lorenz (1992), RSMN already started to increase in the suboptimum SMN range. Almost eighty percent of the variation in RSMN could be accounted for by multiple regression based on SMN supply, crop N uptake and cumulative summer rainfall.

Losses during winter were strongly related to N inputs from RSMN and late summer- or autumn-spread slurry. Leaching losses from cattle slurry were negligibly lower if application was postponed from late summer to autumn and only slightly lower following DCD addition. Lowest leaching losses from slurry were generally associated with spring application. For all treatments (except for the low rate of spring-applied slurry in 1988), concentrations were well above the EC standard for drinking water, however. Observations during winter in the continuous experiment from autumn 1985 to spring 1988, showed that leaching did not account for the total loss. Apparently other processes such as denitrification played a role as well.

In conclusion, addition of nitrification inhibitors to autumn-applied slurry did not improve the N recovery by maize sufficiently to justify recommendation of this practice as an alternative for slurry application in spring. Even with spring application, however, high N losses occurred both during the growing season and after harvest. The soil mineral N supply in spring associated with the highest financial return, resulted in nitrate-N concentrations in the upper groundwater that exceeded the EC standard for drinking water.

Our results indicate that risks of pollution from maize land can be limited by adding N at rates below economically optimum levels. Improved management practices such as N placement (Maddux *et al.*, 1991; Sawyer *et al.*, 1991), conditional post emergence N dressings (Magdoff, 1991) and winter cover crops (Schröder *et al.*, 1992a), seem necessary to ensure that economic and environmental goals can both be realised.

CHAPTER 5

EFFECT OF SPLIT APPLICATIONS OF CATTLE SLURRY AND MINERAL FERTILISER-N ON THE YIELD OF SILAGE MAIZE IN A SLURRY-BASED CROPPING SYSTEM

J.J. Schröder

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5.1 Abstract

The recovery of soil mineral nitrogen (N) by crops, and its subsequent utilisation for dry matter (DM) production may be increased when the application of N is postponed until after crop emergence. The significance of this strategy for silage maize was studied in nine field experiments on Dutch sandy soils from 1983 to 1988.

In five experiments the effect of slurry applied before planting at a rate of circa 66 m^3 ha^{-1}, was compared to the effect of a similar rate of which half was applied before planting and half at the 4-6 leaf stage. In the 4-6 leaf stage slurry was either injected or banded.

In four other experiments the effect of mineral fertiliser-N splitting was studied. In these experiments, 30 m^3 ha^{-1} cattle slurry, applied before planting, was supplemented with mineral fertiliser-N at rates ranging from 40 to 160 kg ha^{-1}, either fully applied before crop emergence or split. When split, 40 kg ha^{-1} of the mineral fertiliser-N rate was banded at the 4-6 leaf stage.

According to balance sheet calculations, substantial losses of slurry N and mineral fertiliser-N occurred during the growing season. Losses were compensated for, however, by apparent mineralisation, ranging from 0.34 to 0.77 kg N ha^{-1} d^{-1}.

Split applications of cattle slurry had a significant positive effect on the DM yield in two out of five experiments compared to the conventional non-split application, but only when the post-emergence slurry application was banded which is not in accordance with present legislation. Split applications of mineral fertiliser-N had a significant positive effect in one experiment where rainfall was excessive but not in the others. The results provide insufficient evidence to recommend farmers to split applications. Soil mineral N sampling at the 4-6 leaf stage should hence be considered a control on the appropriateness of early N applications after exceptional weather conditions rather than a routine observation on which the post-emergence N dressing is to be based in a deliberate splitting strategy. Our data suggest that the financial return of a 40 kg ha^{-1} supplementation with mineral fertiliser-N, was questionable when more than 175 kg N ha^{-1} were found in the upper 0.6 m soil layer at the 4-6 leaf stage.

Key words: cattle slurry, fertiliser splitting, nitrogen, recovery, residual nitrogen, *Zea mays* L.

5.2 Introduction

Timing is one of the factors determining how well fertiliser nitrogen (N) is utilised for crop production. When applied too early, especially nitrate-N may leach or denitrify (Blackmer *et al.*, 1989; Magdoff, 1991; Binford *et al.*, 1992a; Torbert *et al.*, 1993). Even with manure such losses may occur, as half of the N in commonly used animal slurries is ammoniacal which is rapidly nitrified (Van Dijk & Sturm, 1983; Schröder *et al.*, 1993).

Synchronisation of soil N supply and crop N demand can be improved by split applications of N, as demonstrated for winter wheat in various countries (Dilz *et al.*, 1982). Such a strategy may be appropriate for maize too, as most N is not taken up earlier than from at least six weeks after emergence (Hanway, 1962). However, a partial postponement of N applications may expose a maize crop to temporary N deficiency during the first few weeks after its emergence. Moreover, split applications require appropriate equipment and suitable soil and weather conditions to become effective and to carry them out without crop damage (Blackmer *et al.*, 1992). The latter is of special concern when slurry is the source of N since heavy equipment is needed for its application. Incorporation or injection, legally required at present in The Netherlands to avoid ammonia (NH_3) volatilisation losses from slurry, may damage the root system even more although risks can be minimised if slurry is placed in between the maize rows. From a plant nutrition perspective, however, this position is less effective, as root length densities between the rows can remain extremely low for a long period (Sawyer *et al.*, 1991; Schröder *et al.*, 1996a; Schröder *et al.*, 1997b).

Results from experiments on fertiliser splitting in maize are often difficult to interpret as timing treatments are frequently intertwined with placement treatments, since each application time has its own horizontal and vertical placement options. This makes it difficult to attribute the observed effects to timing only (e.g. Eckert, 1987; Timmons & Baker, 1992; Salardini *et al.*, 1992). Experiments have shown variable responses of maize yields to split N applications. Bundy *et al.* (1992) and Menelik *et al.* (1994) did not observe clear benefits of split applications. Others found a negative response which was either attributed to a negative effect of withheld N, to ineffectivity of postponed applications or to combinations of both (Bacon & Thompson, 1984; Bassel *et al.*, 1987; Jokela & Randall, 1989; Gascho & Hook, 1991; Jokela, 1992a; Reeves *et al.*, 1993). A positive response to N splitting was observed in experiments where rainfall favoured early leaching during the growing season (Primost, 1964; Welch *et al.*, 1971; Reeves & Touchton, 1986; Maidl, 1990; Killorn & Zourarakis, 1992; Torbert *et al.*, 1993). In all these experiments mineral fertiliser-N was used. Beauchamp (1983) demonstrated, however, that maize yields can also respond positively to post-emergence applications of cattle slurry.

The aforementioned references indicate that benefits of N splitting are not always evident. Apparently, benefits depend on various factors such as soil type, weather, mineralisation, crop stage, rooting patterns and placement options, leaving maize growers puzzled. This paper reports results from nine field experiments that were set up to elucidate the potential merits of N splitting under Dutch conditions. Slurry was considered an indispensable component of the systems that were to be tested, as slurry was and still is the major source of plant nutrients for maize in The Netherlands. Moreover, the gradual release of N from the organic fraction of the slurry (Whitmore & Schröder, 1996), may itself contribute to a better synchronisation which possibly makes it less relevant to split the application. For this reason, slurry applications at usual rates were included in the experiments. The objective of the experiments was to find out whether maize N uptake and dry matter (DM) yield responded better to N supplied in a split application than to N supplied in a conventional non-split application.

5.3 Materials and methods

5.3.1 Experimental sites

From 1983 to 1988 nine trials (referred to as Experiments 1-9) were carried out by the Research Station for Arable Farming and Field Production of Vegetables (PAGV) on six sites (referred to as A-F) in The Netherlands. All sites were located on sandy soils with organic matter contents ranging from 1.7 to 6.8%. Soil P and K contents were generally high (Table 5.1). On these soils, maize roots concentrate in the top 0.4-0.6 m due to a low organic matter content and high bulk density in deeper layers. On all sites, except for site D, animal slurry had been applied regularly in the past, except for the year preceding the experiments. On all sites maize was grown in the previous year, except for site D where gladiolus was grown.

Table 5.1. Soil characteristics of the 0-0.25 m layer at the onset of the experiments.

Site	Experiments	Years	Soil texture	Potential rooting depth (m)	Organic matter (%)	P [a] (mg l^{-1})	K [b] (mg kg^{-1})	pH-KCl
A	1 and 2	1983-1984	loamy sand	0.6	3.0	27	12	5.3
B	3	1983	sand	0.6	2.7	30	11	6.0
C	4 and 5	1986-1987	sand	0.4	6.7	24	7	4.7
D	6	1985	loamy sand	0.5	1.7	17	8	7.5
E	7 and 8	1986-1987	sand	0.6	3.3	26	11	5.5
F	9	1987	sand	0.4	6.8	20	4	4.6

[a] after extraction with 1:60 (soil):(water) volume ratio

[b] after extraction with 1:10 (soil):(0.1 N HCl / 0.4 N oxalate) weight ratio

5.3.2 Design and plot size

All experiments had a randomised complete block design with three (Experiments 1-5) or four (Experiments 6-9) replicates. Plot size was 6 x 12 m (10 m on site C). Only the inner 3 x 10 m (8 m on site C) of this area was used for soil and crop observations. Treatments remained on the same plot when consecutive experiments were carried out on the same site (site A, C, E).

5.3.3 Treatments

Treatments in Experiments 1-5 focused on the effect of split slurry applications. The experiments included slurry applications at a rate of circa 66 m^3 ha^{-1}, either fully applied before planting in March or April or split. When split, half of the rate was applied before planting and half at the 4-6 (fully expanded) leaf stage (Table 5.2). At that stage crop height just allows field traffic without direct contact between machinery and plants. A control treatment without slurry and a treatment with 100 kg ha^{-1} mineral fertiliser-N (calcium ammonium nitrate (CAN), broadcast within one week after planting) were included in all five experiments.

Table 5.2. Mineral fertiliser-N and slurry application rates included in the experiments, partitioning over application moments and method of post-emergence application; a listing of the treatments used for the assessment of soil mineral N (SMN) at various moments is given last column (T1 = before the pre-planting application of slurry, T2 = at the 4-6 leaf stage, T3 = at harvest).

Experiment		Pre-emergence	Pre-planting	Post-emergence			SMN-
		fertiliser-N (kg ha^{-1})	slurry (m^3 ha^{-1})	Fertiliser-N (kg ha^{-1})	Slurry (m^3 ha^{-1})	Method	sampling
1 - 5	control	0	0	-	0		T1, T2, T3
	non-split	0	66	-	0		T1, T2, T3
	split	0	33	-	33	injected	T1, T2, T3
	split	0	33	-	33	banded	T1, T2[a], T3[a]
	non-split	100	0	-	0		
6-9	control	0	30	0	-		T1, T2, T3
	split	0	30	40	-	banded	
	non-split	40	30	0	-		T1, T2
	split	40	30	40	-	banded	
	non-split	80	30	0	-		T1, T2
	split	80	30	40	-	banded	
	non-split	120	30	0	-		T1, T2
	split	120	30	40	-	banded	T3
	non-split	160	30	0	-		T1, T2, T3

[a] except for Experiments 1-3

Treatments in Experiments 6-9 focused on the effect of split mineral fertiliser-N applications. The experiments included mineral fertiliser-N rates (CAN) ranging from 40 to 160 kg ha^{-1}, either fully applied before crop emergence (broadcast within one week after planting) or split. When split, 40 kg N ha^{-1} was applied at the 4-6 leaf stage (Table 5.2). Before planting, 30 m^3 cattle slurry ha^{-1} was applied in March-April to all treatments which included a control treatment without mineral fertiliser-N.

Slurry applied before planting was evenly broadcast and incorporated within 24 and 6 hours in Experiments 1-3 and 6-9, respectively, and injected (tine distance 0.5 m, depth 0.2 m) in Experiments 4 and 5. These basal slurry applications took place 29 days before planting in Experiment 1 and 3-14 days before planting in all other experiments. Slurry applications before planting were followed by mould board ploughing and seed bed preparation with a packer.

Slurry applied at the 4-6 leaf stage was banded between the maize rows (band width 0.45 m) or injected midway between the rows (depth 0.2 m) (Table 5.2). Mineral fertiliser-N applied at the 4-6 leaf stage was banded between the rows (band width 0.6 m). Applications were carried out in the second half of June when crop height was 0.3-0.5 m. In Experiment 4, however, the crop had reached a height of 0.65 m (8 leaf stage).

Cattle slurry contained on average 97 kg DM, 5.2 kg total N, 2.3 kg ammonium N (NH_4-N), 0.9 kg phosphorus (P) and 5.2 kg potassium (K) m^{-3}. Total inputs of the non-split and split treatments in Experiments 1-5 were reasonably similar within experiments (Table 5.3). The inputs of total-N from slurry in Experiments 6, 7, 8 and 9, amounted to 153, 168, 170 and 127 kg ha^{-1}, respectively, and corresponding NH_4-N inputs were 60, 60, 58 and 43 kg ha^{-1}.

Table 5.3. Total N and NH_4-N applied with slurry (kg ha^{-1}) at the pre-planting and post-emergence application times.

Experiment	Year	Treatment	Pre-planting		Post-emergence	
			total N	NH_4-N	total N	NH_4-N
1	1983	non-split	384	177	0	0
		split	192	88	196	98
2	1984	non-split	368	144	0	0
		split	184	72	200	100
3	1983	non-split	316	191	0	0
		split	158	95	180	95
4	1986	non-split	294	114	0	0
		split	157	61	132	81
5	1987	non-split	333	109	0	0
		split	161	53	172	83

5.3.4 Crop husbandry

Silage maize (*Zea mays* L., cvs. Irla (Experiments 1-3), Clipper (Experiments 4-5) and Vivia (Experiments 6-9)) was planted between April 27 and May 16 in rows 0.75 m apart at a density of 72.000-103.000 plants ha^{-1}. P was annually applied as a subsurface banded starter at a rate of 22-35 kg ha^{-1}. In Experiments 1-3, starters contained also 17 kg N ha^{-1}, wheras P alone was used in all other experiments. Mineral K supplements were applied annually at rates of 125-208 kg ha^{-1}. Sites C and F were limed annually with 3000 kg ha^{-1} in the autumns preceding the experiments. Weeds were controlled chemically with atrazine-containing compounds. Crops were harvested in October when they reached a DM content of about 30%.

5.3.5 Measurements

The amounts of soil mineral N (SMN: NO_3-N +NH_4-N) were measured in the top 0.3 and 0.3-0.6 m layer prior to the application of slurry or mineral fertiliser-N before planting (T1), before the application of slurry or mineral fertiliser-N at the 4-6 leaf stage (T2), and within four days after harvest (T3) in a number of treatments (Table 5.2). Six samples per plot were taken at random (T1) or 0.15-0.20 m from the plant row (T2, T3). Samples were pooled per treatment before analysis by extraction with 1 *N* KCl.
In Experiments 6 and 8, 20 randomly chosen maize stems were collected from each plot at T2. Samples were pooled per treatment and transported to the laboratory at a temperature < 5°C. Subsequently, stem sap was analysed for NO_3-N with a semi-quantitative quick test (Merckoquant 10020).
Dry matter content of mature silage maize was assessed in duplicate in 600 g subsamples of chopped material of 25 randomly sampled plants per plot (Experiments 1-3) or of chopped stover and cob material from 2 x 2 m row length (Experiments 4-9). Fresh weights of these whole plant or plant fraction samples were determined. One subsample was dried for 48 h at 70°C, another for 48 h at 105°C. Subsequently, the remaining plants on each plot were cut and weighed. Crop samples dried at 70°C were pooled per treatment and used for the determination of the Kjeldahl N content.

5.3.6 Definitions

The apparent mineralisation (AM) on control plots (Experiments 1-5) during spring and summer, inclusive of all losses and gains due to atmospheric deposition, was derived from the following balance sheet calculation: (N uptake of the harvested maize + SMN at T3) - (SMN at T1 + mineral fertiliser-N in starter). For the calculation of the AM on the 0 kg mineral fertiliser-N plots in the Experiment 6-9, the balance sheet was slightly adapted: (N uptake of the harvested maize + SMN at T3) - (SMN at T1 + mineral N applied with slurry). It must be noted that the latter definition of AM includes the NH_3 volatilisation losses from the slurry applied at T1 in Experiments 6-9. The daily AM was defined as AM devided by the number of days between samplings and used as an indicator for the native N supplying capacity (including the N effectively supplied by the organic fraction of the slurry in Experiments 6-9).
The apparent N recovery (ANR) of slurry or mineral fertiliser-N was used to indicate how efficiently N was taken up by the crop or to what extent it remained in the crop-soil system. ANR in the crop was defined as the difference in N uptake between a fertilised and a non-fertilised crop and expressed as a percentage of the total N input from slurry or from mineral fertiliser-N. The ANR in the crop and soil together, was defined as the sum of the difference in N uptake between a fertilised and a non-fertilised crop and the difference in the change in SMN between a fertilised and a non-fertilised crop, and expressed as a percentage of the total N input from slurry or from mineral fertiliser-N. As a non-fertilised control treatment was lacking in Experiments 6-9, the N uptake of the 0 kg mineral fertiliser-N treatment was used instead. Therefore, ANR values of Experiments 6-9 pertain to the marginal ANR of mineral fertiliser-N and not the ANR of all N inputs together.

5.3.7 Weather conditions

Average temperature during the growing period (1 May - 1 October) ranged from 13.9 in 1984 to 16.3°C in 1983. Between 1 March and 1 August, all experiments, except for Experiment 4 and 7, were frequently exposed to extremely wet spells (Table 5.4).

Table 5.4. Monthly rainfall in the experiments and the long term (1960-1990) average rainfall (mm) for De Bilt weather station.

Experiment	Year	Month:							
		March	April	May	June	July	Aug.	Sept.	Oct.
1	1983	69	28	150	59	17	26	60	47
2	1984	50	10	145	58	47	6	125	94
3	1983	82	13	137	47	53	21	66	30
4	1986	70	45	45	56	34	49	29	101
5	1987	80	19	85	74	84	86	72	88
6	1985	51	35	90	167	109	91	45	26
7	1986	83	27	62	64	65	53	60	79
8	1987	87	20	63	97	127	84	46	87
9	1987	74	24	67	99	89	62	65	79
De Bilt	1960-1990	47	50	58	63	89	82	66	60

5.4 Results

5.4.1 Apparent mineralisation

SMN before planting at T1 in the upper 0.6 m soil layer averaged 33 (range 12-60) kg ha^{-1}. The apparent daily N mineralisation between T1 and T3 on the control plots of Experiments 1-5, ranged from 0.62-0.73 kg ha^{-1}. The apparent daily mineralisation (inclusive NH_3 volatilisation losses from slurry) in the 0 mineral fertiliser-N treatments of Experiments 6, 7, 8 and 9, amounted to 0.34, 0.77, 0.57 and 0.40 kg N ha^{-1}, respectively.

5.4.2 Effects of slurry splitting (Experiments 1-5)

DM yields responded positively (P<0.05) to slurry or mineral fertiliser-N in all experiments. Significant differences within slurry treatments were only found in Experiments 1, 4 and 5. In Experiment 1, slurry banding reduced yields compared to the treatment where the post-emergence application was injected. In Experiment 4 and 5, the banded split applications resulted in higher yields compared to the treatment where slurry was not split. On average, however, DM yields were not significantly affected by splitting and the method of slurry application (Table 5.5).

In Experiments 4 and 5, the apparent mineralisation (AM) could be calculated for the banded and for the injected split slurry treatments according to the definition used in Experiments 6-9 (see materials and methods). The AM between T1 and T3 was 25 and 12 kg N ha^{-1} larger for the injection treatment than for the banded treatment in Experiments 4 and 5, respectively. This calculated difference was probably due to a higher NH_3 volatilisation in the banded treatment compared to the injected treatment as the definition of AM included such losses. When related to the NH_4-N

Table 5.5. DM yield of silage maize (t ha^{-1}) as affected by the method of slurry application (Experiments 1-5).

Experiment	Year	Pre-emergence mineral fertiliser-N rate (kg ha^{-1})	Slurry application method: no slurry	non-split slurry	split slurry: injected	banded	LSD (P<0.05)
1	1983	0	11.06	12.42	13.71	10.71	2.36
		100	13.10	-	-	-	
2	1984	0	8.36	9.07	8.96	8.28	1.06
		100	9.48	-	-	-	
3	1983	0	11.59	15.23	15.09	15.83	1.14
		100	15.01	-	-	-	
4	1986	0	10.03	11.45	11.82	12.96	1.43
		100	11.72	-	-	-	
5	1987	0	9.35	10.63	11.15	11.42	0.57
		100	10.60	-	-	-	
	mean	0	10.08	11.76	12.15	11.84	0.69
		100	11.98	-	-	-	

input (Table 5.3), losses were equivalent to 31% in Experiment 4 and 14% in Experiment 5. Despite these additional losses, banding had a positive effect on maize yields compared to treatments where slurry was injected.
The ANR of slurry in the crop from T1 to T3, amounted to on average 14-15% without consistent differences between non-split or split applications (Table 5.6). The corresponding ANR of 100 kg ha^{-1} mineral fertiliser-N (data not shown here) averaged 35% (range 24-53). When changes of SMN were also accounted for, ANR's of slurry increased to 30-31%. The ANR's in crop and soil together during the first part of the growing season (T1-T2), were generally larger than those for the whole season (T1-T3), suggesting that losses also occurred after the 4-6 leaf stage. The ANR between T1 and T2 was relatively low in 1983 (extremely wet spring) and relatively high in 1986 and 1987 (dry spring).

Table 5.6. Apparent recoveries (%) of total slurry-N (Experiments 1-5) and marginal apparent recoveries (%) of 160 kg N ha^{-1} mineral fertiliser-N (Experiments 6-9), as affected by splitting slurry or mineral fertiliser-N applications; From March-April (T1) to the 4-6 leaf stage (T2) in the harvested crop and soil (0.6 m layer) together, and from T1 to the harvest of silage maize (T3) in the harvested crop and soil (0.6 m layer) together, or in the crop only.

Experiment	Year	Period, system boundaries and application method:					
		T1-T2, crop+soil		T1-T3, crop+soil		T1-T3, crop only	
		non-split	split	non-split	split	non-split	split
1	1983	9	7	24	20	6	12
2	1984	25	32	16	10	5	5
3	1983	27	17	38	33	27	25
4	1986	88	57	49	66	21	21
5	1987	65	77	22	25	11	13
average 1-5		43	38	30	31	14	15
6	1985	57	66	49	48	43	36
7	1986	96	81	73	128	26	22
8	1987	94	117	29	37	11	13
9	1987	161	188	50	58	13	16
average 6-9		102	113	50	68	23	22

5.4.3 Effects of mineral fertiliser splitting (Experiments 6-9)

Maize DM yields responded strongly to mineral fertiliser-N in Experiment 6 where maximum yields were attained at the 160 kg N ha^{-1} rate. Especially at lower N rates, split treatments outyielded non-split treatments slightly. In the other three experiments, maximum yields were attained at the 80 kg N ha^{-1} rate and a partial postponement of the application of N (up to a rate of 80 kg N ha^{-1}) tended to have a negative effect (not significant) on DM yields (Table 5.7).

Mineral fertiliser-N applications at the 4-6 leaf stage increased yields when

Table 5.7. DM yield of silage maize (t ha^{-1}) as affected by the application rate and splitting of mineral fertiliser-N, in addition to a basal cattle slurry application of 30 m^3 ha^{-1} before planting.

Experiment	Year	Total fertiliser-N rate (kg ha^{-1})	Application: non-split	Application: split	LSD ($P<0.05$)
6	1985	0	13.02	-	1.00
		40	14.06	14.44	
		80	15.04	15.43	
		120	15.87	16.00	
		160	16.18	15.86	
7	1986	0	15.15	-	1.00
		40	16.27	15.52	
		80	16.52	16.33	
		120	16.47	16.56	
		160	16.42	16.46	
8	1987	0	10.56	-	0.95
		40	10.95	10.68	
		80	11.15	10.73	
		120	10.93	11.07	
		160	10.96	11.16	
9	1987	0	9.10	-	0.52
		40	9.56	9.44	
		80	9.81	9.58	
		120	9.53	9.95	
		160	9.56	9.84	

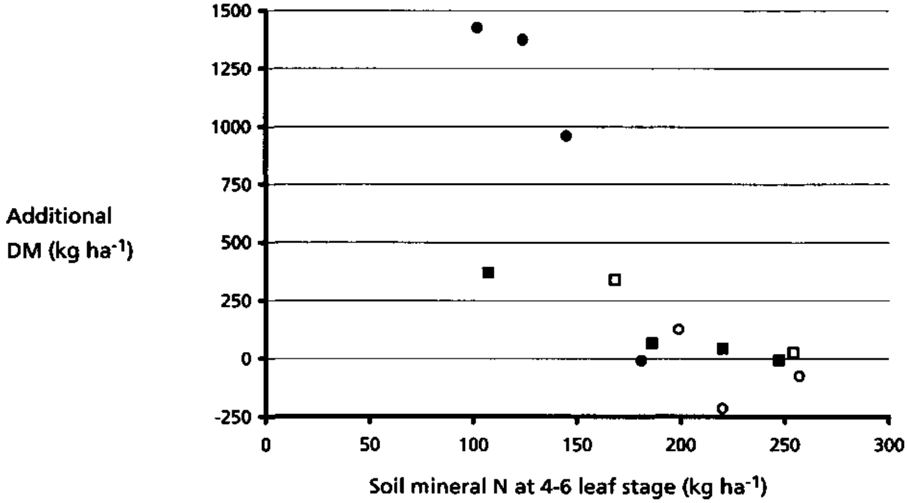

Figure 5.1. Additional silage maize DM production (kg ha^{-1}) resulting from a post-emergence mineral fertiliser application of 40 kg N ha^{-1}, as related to the soil mineral N supply at the 4-6 leaf stage (kg ha^{-1}, 0.6 m) in Experiment 6 (●), 7 (O), 8 (■) and 9 (□).

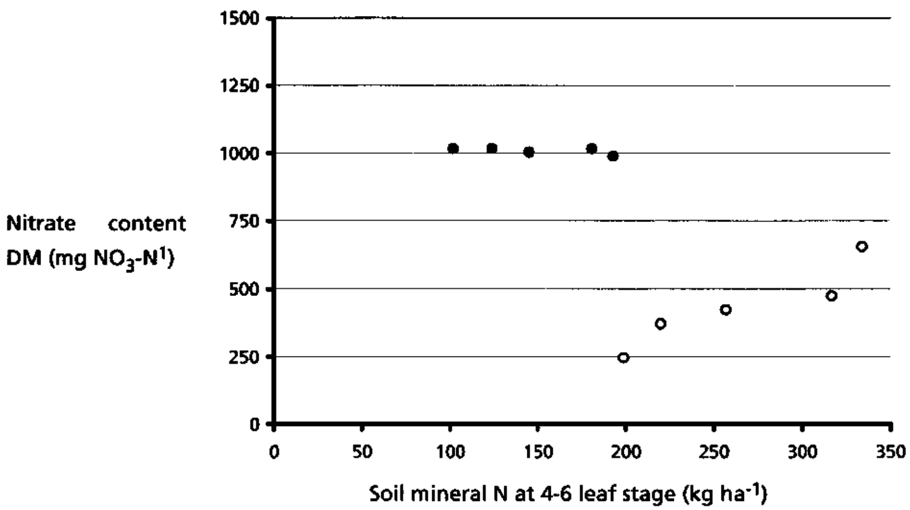

Figure 5.2. Nitrate content (mg NO_3-N l^{-1}) in the stem sap of maize at the 4-6 leaf stage, as related to the soil mineral N supply at that stage (kg ha^{-1}, 0.6 m) in Experiment 6 (●) and 8 (O).

soil mineral N supply was low (Figure 5.1). Nitrate concentrations in the stem sap of young maize plants did not consistently reflect the availability of SMN or the crop demand for N, as reflected by the significantly ($P<0.01$) different slopes and intercepts of the response in individual experiments. Concentrations were relatively low in Experiment 8 where maize yields responded weakly to N, whereas concentrations were high but not related to SMN in Experiment 6 where maize yields were most responsive to N (Figure 5.2).

On average, only 22-23% of 160 kg N ha^{-1} mineral fertiliser-N was recovered in the harvested crop material at T3 without consistent differences between the non-split and split treatments (Table 5.6). When 80 kg N ha^{-1} mineral fertiliser-N was applied (individual data not shown), marginal ANR's averaged 34% (range 12-48) and 30% (range 3-54) for non-split and split treatments, respectively. When changes in SMN with time were included as well, on average at least 42% of the 160 kg N ha^{-1} mineral fertiliser-N was not accounted for except for Experiment 7 where summer rainfall was low.

At T2, however, on average, most fertiliser N was recovered. Recoveries at T2 were unrealisticly high in Experiment 9. Possibly, sampling schemes for SMN took insufficient account of lateral gradients. This may have overestimated the amounts of SMN actually available on a whole area basis.

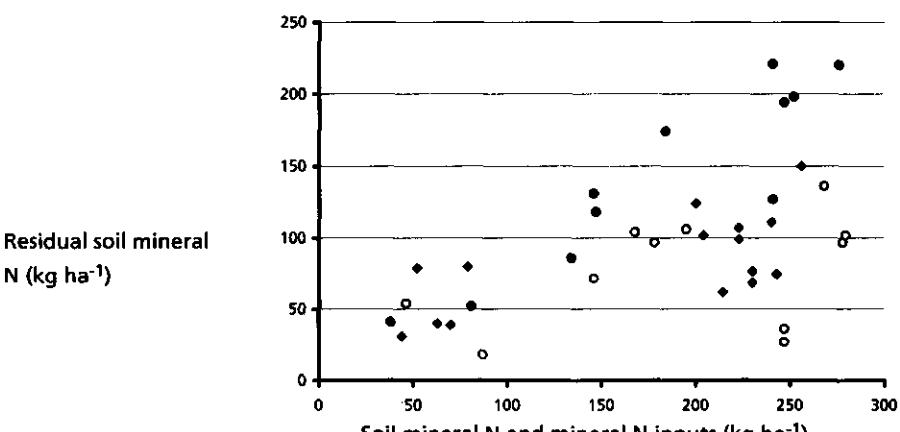

Figure 5.3. Residual soil mineral N (kg ha^{-1}, 0.6 m soil layer) after the harvest of silage maize, as affected by the sum of mineral N in the upper 0.6 m soil layer before the application of fertiliser-N or slurry and mineral N inputs from fertiliser and slurry (kg ha^{-1}); cumulative rainfall between May 1 and silage maize harvest <200 mm (●), 200-500 mm (◆), >500 mm (O).

5.4.4 Residual SMN

Splitting the application of slurry (Experiments 1-5) had no effect on the amount of residual SMN. Splitting the application of mineral fertiliser-N (Experiments 6-9) increased residual SMN insignificantly (individual data not shown).
Residual SMN recorded at T3 was strongly related to the sum of SMN at T1 and mineral N inputs from either slurry or mineral fertiliser. Relatively large amounts were found after the dry summer in Experiments 4 and 7, whereas smaller amounts were observed after the extremely wet summer in Experiments 6 and 8 (Figure 5.3). Variance accounted for increased from 29 to 57% if a linear regression model relating the residual SMN to the sum of SMN at T1 and mineral N inputs, was extended to include cumulative rainfall between May 1st and T3 sampling. A 100 mm increase of rainfall reduced residual SMN with 25 kg ha^{-1} (Table 5.8).

5.5 Discussion

Results from nine field experiments indicated that only a small fraction of N inputs from cattle slurry or mineral fertiliser-N was recovered in the maize crop or in the soil at the end of the growing season. The poor recovery of N in the crop resulted predominantly from the relatively large N inputs, as indicated by the increase of the crop recovery values at lower N inputs. When slurry was the source of N (Experiments 1-5), on average, 30% of the total N input from 66 m^3 ha^{-1} slurry, was recovered in crop and soil all together. This low value can not entirely be explained by an incomplete decomposition of organic N in the slurry, as half of the N in the slurry was ammoniacal. Possibly, recoveries from slurry were also low due to NH_3 volatilisation losses (Döhler, 1991) and enlarged denitrification losses (Guenzi *et al.*, 1978) associated with the use of slurry. However, when mineral fertiliser was the source of N, recoveries were also low. In Experiments 1-5, the recovery of 100 kg ha^{-1} mineral fertiliser-N by the crop averaged 35%. In Experiments 6-9, the marginal recovery of 160 kg mineral fertiliser-N ha^{-1} in the crop alone, and in the crop and soil all together, averaged 22-23% and 50-68%, respectively. Recoveries of both slurry and mineral fertiliser-N were

Table 5.8. Linear regression models relating post-harvest residual soil mineral N (upper 0.6 m soil layer) (RSMN, kg ha^{-1}) to the sum (SUMN, kg ha^{-1}) of pre-planting mineral N (upper 0.6 m soil layer) and mineral N inputs from fertiliser and slurry or to SUMN and the cumulative rainfall (RAIN, mm) between 1 May and the RSMN sampling date: RSMN = a + (b x SUMN) + (c x RAIN).

RSMN = a + (b x SUMN)		RSMN = a + (b x SUMN) + (c x RAIN)	
Estimate	a: 31* [1]	Estimate	a: 123***
	b: 0.38***		b: 0.39***
			c: -0.25***
Variance accounted for (%): 29		Variance accounted for (%): 57	

1 * P<0.10, ***P<0.01

depressed by excessive rainfall. This was probably due to leaching or denitrification losses during the growing season as earlier reported by Schröder *et al.* (1993) and Torbert *et al.* (1993).

Excessive rainfall early in the season, as encountered in some of the experiments, may favour a positive response to split mineral fertiliser applications (Welch *et al.*, 1971; Killorn & Zourarakis, 1992; Torbert *et al.*, 1993). However, splitting the application of slurry had a significant positive effect in only two of the five experiments and only when the post-emergence application was banded instead of injected. Banding, however, is no longer permitted by Dutch legislation because slurry banding may lead to NH_3 volatilisation. In the other three experiments effects of splitting were insignificant and splitting even reduced yields significantly in one experiment, when the post-emergence application was not injected. Apparently, potential benefits of post-emergence slurry applications may have been counteracted by root damage (especially when injected) or NH_3 volatilisation (especially when banded). The latter was supported by the calculated difference between the N balance sheets of injected and banded slurry applications, suggesting that 31% and 14% of the NH_4-N input of banded slurry was lost in Experiments 4 and 5, respectively.

In the experiments on the splitting of mineral fertiliser-N, split applications had a negative effect on DM-production unless rainfall was excessive. This negative effect was strongest at the lower N rates, which is in agreement with the results of Salardini *et al.* (1992). Probably, N must be applied in due time to assure a sufficient concentration near the maize roots (Schröder *et al.*, 1996a), be it at the expense of leaching risks early in the season. In the course of time, the need for additional fertiliser-N apparently becomes less, as the root system extends into soil compartments that were as yet unexplored (Schröder *et al.*, 1996a; Schröder *et al.*, 1997b) and mineralisation contributes to the availability of N (Whitmore & Schröder, 1996). The latter was confirmed by balance sheet calculations of the control plots of Experiments 1-5 confirming the evolution of appreciable amounts of N. The apparent daily mineralisation amounted to 0.4-0.8 kg ha^{-1} in eight out of nine experiments. Such values fall in the range reported by others (Greenwood *et al.*, 1985; Magdoff, 1991; Schröder *et al.*, 1993). Maize in Experiment 6 responded positively to split mineral fertiliser-N applications. This experiment took place on a site where the soil organic matter content was low and organic manures had not been applied in the recent past, contrary to what is common on maize land in The Netherlands. Moreover, the site was exposed to 156 mm more rainfall than usual between May and July. This was reflected in an apparent daily mineralisation of only 0.3 kg ha^{-1}. These conditions can have contributed to the positive yield response to split N applications.

The data presented here do generally not support the suggested benefits of split mineral fertiliser-N or slurry applications for maize. However, in the near future, legislation will force maize growers to reduce N inputs and this will inevitably reduce mineralisation rates (Whitmore & Schröder, 1996). Under such conditions early losses may have more serious consequences which may increase the potential benefits of split applications.

In a cold and wet spring mineral fertiliser-N or slurry applied before crop emergence, may be lost or at least unavailable for a shallowly rooting maize crop and urge for supplementation. The results from Experiments 6-9 indicate that a supplementation with 40 kg N ha^{-1} yielded less than the 200 kg DM ha^{-1} needed to break even (at a price ratio of 5 kg silage DM per kg N), when more than about 175 kg N ha^{-1} was found in the upper 0.6 m soil layer. This value, comparable to the recommendation of Binford *et al.* (1992a), may be used as a criterion in decision making.

The nitrate contents of maize stems appeared to be an unreliable indicator for the N requirements of a maize crop, as earlier concluded by Fox *et al.* (1989) and Binford *et al.* (1992b). Apparently, other factors than just N determine the nitrate concentration of maize stalks. In agreement with the results of Iversen *et al.* (1985a), high nitrate concentrations were found under gloomy weather conditions (Experiment 6) and low concentrations under bright weather conditions (Experiment 8).

Jokela & Randall (1989) reported that delayed N applications may reduce early losses but promote losses at the end of the season. Splitting mineral fertiliser-N applications resulted in an insignificant increase of residual SMN in our experiments. Splitting slurry applications did not lead to such an increase of residual SMN. However, this can be an artifact, as samples were taken 0.15-0.20 m from the former maize row. Hence, they did not include the part of the profile where slurry had been injected at the 4-6 leaf stage. As horizontal N gradients may persists until after harvest (Clay *et al.*, 1995; Schröder *et al.*, 1996a; Schröder *et al.*, 1997b), the sampling procedure in the present experiments may have slightly underestimated residual SMN in case of split slurry applications.

Due to losses over summer, excess N was only partly recovered as residual SMN. Residual SMN was positively related to the mineral N inputs and negatively related to rainfall during the growing season. The pronounced effect of rainfall was also found in other experiments with maize on sandy soils (Schröder *et al.*, 1993; Schröder *et al.*, 1996b).

In conclusion, split applications of cattle slurry or mineral fertiliser-N did not increase the DM yield of silage maize when compared to pre-plant applications in trials where soils, weather and management represented Dutch maize growing conditions. Hence, N splitting is not considered a strategy superior over the conventional pre-planting application of slurry and pre-emergence application of fertiliser-N.

CHAPTER 6

EFFECTS OF COVER CROPS ON THE NITROGEN FLUXES IN A SILAGE MAIZE PRODUCTION SYSTEM

J.J. Schröder, W. van Dijk and W.J.M. de Groot

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6.1 Abstract

Rye and grass cover crops can potentially intercept residual soil mineral nitrogen (SMN), reduce overwinter leaching, transfer SMN to next growing seasons and reduce the fertiliser need of subsequent crops. These aspects were studied for 6 years in continuous silage maize production systems with nitrogen (N) input levels ranging from 20 to 304 kg total N ha^{-1}, on a sandy soil in The Netherlands.

Rye and grass cover crops were able to absorb on average 40 kg N ha^{-1} in the aboveground plant parts. The actual N uptake was largely determined by winter temperatures and hardly by residual SMN. At low N input levels cover crops reduced N leaching in accordance with their N uptake. At high N input levels, however, the reduction of leaching losses exceeded the storage capacity of the cover crop, suggesting that cover cropping can have stimulated the loss of N via denitrification or immobilisation.

Cover crops had no positive effect on maize yields at larger N rates and under these conditions cover crops did not improve the conversion of SMN into crop N. This was only partly reflected by an increase of residual SMN on plots where cover crops had been incorporated, as a large part of the excess N on maize was already lost during the growing season. In N deficient maize production systems, however, cover crops increased the dry matter yield of maize. Their effect was equivalent to the effect of fertiliser N rates amounting to 105% and 44% of the aboveground N in rye and grass, respectively.

In the first few years cover crops decomposed incompletely during the growing season following their incorporation. In the course of the years, however, effects on subsequent maize crops increased. This supports the hypothesis that effects of cover crops can cumulate when grown repeatedly. Averaged over the 6 years, 115% and 73% of the aboveground rye N and grass N, respectively, were recovered in the crop-soil system.

Keywords: apparent recovery, cover crop, fertiliser value, maize, nitrate leaching, nitrogen

6.2 Introduction

Mineral nitrogen (N) remaining in the soil at the end of the growing season, may leach during winter and contaminate surface and groundwater. Maize crops can leave large amounts of soil mineral N (SMN). Excessive use of organic and mineral fertilisers on maize land is only one of the reasons (Schlegel *et al.*, 1996). Crop characteristics, however, also play a role. Soil organic N mineralised after the end of July, accumulates in the soil due to an early cessation of N uptake (e.g. Pollmer *et al.*, 1979). Moreover, current row spacings of 0.75 m and a limited horizontal root extension (Barber & Kovar, 1991) may lead to an incomplete exploitation of the inter-row soil volume (Aufhammer *et al.*, 1991; Clay *et al.*, 1995). Maize responds positively to large N concentrations in the rooted soil volume (Schröder & Dilz, 1987; Touchton, 1988; Maddux *et al.*, 1991; Sawyer *et al.*, 1991). Therefore, an economically optimal N supply may be associated with more residual SMN than is environmentally desirable (Jokela & Randall, 1989; Jokela, 1992a; Schröder *et al.*, 1993; Vanotti & Bundy, 1994a). Such a situation demands the development of cropping techniques that either avoid the accumulation of residual SMN or reduce the risk of leaching.

Cover crops can take up residual SMN and reduce the downward movement of nitrate due to their transpiration (Steffens & Vetter, 1984; Martinez & Guiraud, 1990; McCracken *et al.*, 1994). However, maize is harvested late in the season and growing conditions after maize are unfavourable compared to those after crops that allow earlier sowing (Schweiger, 1967; Eiers & Hartmann, 1988). Undersown cover crops may therefore perform better than cover crops sown after the harvest of maize. If undersown cover crops are planted too early, however, they may compete for N and water with maize (Stemann & Lütke Entrup, 1991).

N uptake by cover crops will only reduce leaching risks in the long run when their decomposition is properly synchronised with the demands of subsequent crops and when their contribution to the N supply of these crops is taken account of in deciding on subsequent rates of fertiliser N. If not, losses are only postponed. Cover crops have a residual nature and research questions need to be addressed in experiments lasting more than just one season.

From 1988 to 1994 we conducted a long-term field experiment to find out how much residual SMN left by maize crops can be intercepted by cover crops that are either undersown in maize or sown after its harvest.

In addition to it we studied the effects of these cover crops on nitrate leaching and the N uptake and dry matter yield of subsequent maize crops.

6.3 Materials and methods

6.3.1 Soil characteristics

The experiment was carried out in Heino (52° 26' N, 6° 14' E), The Netherlands, on a sandy soil during the period 1988-1994. Soil characteristics are presented in Table 6.1. Rooting on the experimental site concentrated in the top 0.3 m due to a penetrometer resistance of 3 MPa in the deeper layers. The average depth of the groundwater table is 0.85 and 1.60 m during winter and summer, respectively. Excess precipitation is discharged vertically through the profile without significant horizontal transport. Uprise of water from the groundwater does not occur. Pedological and hydrological details are given in Schröder *et al.* (1992a).

In the years preceding the start of the experiment, the site had been used for silage maize production and cattle slurry was regularly applied during that period at annual rates of 50-70 m^3 ha^{-1}. No organic or mineral fertilisers were applied during the 6 months prior to the experiment.

6.3.2 Treatments

The experiment was set up as a split plot design in 4 replicates with 3 cover crop treatments on the mainplots and 5 N application rates on the subplots. Treatments remained on the same plots during the experimental period. Subplot size measured 14 m x 6 m.

Cover crop treatments included fallow, rye (*Secale cereale* L., cv. Admiraal) and Italian ryegrass (*Lolium multiflorum* L., cv. Combita). Fallow plots were weed free during winter. Italian ryegrass was sown in the first half of June as a 0.45 m wide strip between the maize rows (crop height approximately 0.4 m) at a rate of 30 kg ha^{-1}. In the last year of the experiment, no undersowing of grass took place. Rye was sown immediately after harvest of maize at a rate of 200 kg ha^{-1} between September 22 and 28 except for 1993 when sowing had to be postponed until October 10.

Table 6.1. Soil characteristics of upper 0.2 m of the sandy soil in Heino.

organic matter (%)	silt (%)	total N (%)	water soluble P (mg/liter)	exchangeable K (mg/100g)	exchangeable Mg (mg/100g)	pH-KCl
3.1	7	0.107	30	6.6	4.3	4.6

Table 6.2. Annual treatments on subplots.

Code	Fertiliser N ($kg\ ha^{-1}$)		Slurry N ($kg\ ha^{-1}$)	
	broadcast	side dressing	NH_4-N	organic N
N1	0	20	0	0
N2	0	20	74*	90*
N3	40	20	74*	90*
N4	80	20	74*	90*
N5	120	20	74*	90*

* in 1988 and 1989 116 kg NH_4-N and 109 kg organic N $ha^{-1}\ yr^{-1}$ were applied

The cover crops were mechanically destroyed at the end of March-beginning of April with a rotavator to avoid further loss of soil moisture and to stimulate decomposition. In 1989 the destruction of rye was postponed to the end of April. Crop residues were completely incorporated into the soil by a mould board plough (ploughing depth 0.25 m) plus packer in the second half of April.

Treatments on the subplots included 5 combinations of broadcast applied fertiliser N (calcium ammonium nitrate) and cattle slurry N, including a control that only received a subsurface side dressing of 20 kg fertiliser N ha^{-1}. Treatments of the subplots are referred to as N1-N5 (Table 6.2).

Cattle slurry was injected (tine width 0.5 m, depth 0.15 m) between cover crop destruction and ploughing, 7-13 days before maize planting. Injection was carried out with a precision injector especially developed for field trials. From 1990 the application rate was reduced from 45 to 33 $m^3\ ha^{-1}\ yr^{-1}$. Cattle slurry contained on average 96 kg dry matter, 5.0 kg total N, 2.3 kg

NH_4-N, 0.8 kg P and 5.7 kg K m^{-3}. Fertiliser N was broadcast manually within several days after maize planting.

6.3.3 Crop husbandry

Silage maize (*Zea mays* L., cv. LG 2080) was planted between April 22 and May 4 on all subplots resulting in final plant densities of 9.9-12.0 plants m^{-2}. Within years, plant densities were similar in all treatments (P>0.98).

Weeds were successfully controlled with a pre-emergence application of aclonifen, a post-emergence application of pyridate, bromoxynil or bentazone, and hoeing. Maize was harvested between September 14 and September 28. Subsequently, the soil was loosened with a rigid tine cultivator with the exception of the plots with undersown grass.

All plots received a fertiliser dressing of 9 kg P (side dressing) and 110 kg K ha^{-1} yr^{-1} in spring. Additionally, subplots without slurry application (N1) received 27 kg P, 140 kg K and 18 kg Mg ha^{-1} yr^{-1} to compensate for the P, K and Mg applied with manure on N2-N5 plots. The site was limed in autumn whenever necessary.

6.3.4 Measurements

Each year slurry was analysed in duplicate for its dry matter, NH_4-N, organic N, P and K contents. Soil samples from N1, N2 and N5 subplots were taken annually in April before the incorporation of cover crops and the application of fertiliser or manure (T1) and in September (T2). They were analysed for SMN (i.e. NO_3-N and NH_4-N). Six core samples were taken per subplot at random (T1) or at a distance of 0.15-0.2 m from the plant row (T2) to a total depth of 0.6 m. From September 1989 onwards, the 0.6-1.0 m layer of fallow and grass covered N1 and N5 subplots was also sampled. Unless stated otherwise, SMN data refer to the 0.6 m sampling, only. Samples were pooled per treatment before analysis.

Dry matter yields of cover crops were determined just before their destruction in spring by weighing the aboveground fresh material from a net area of 9 m^2 per subplot. Grass yields referred to the weighted average of the grass-covered inter-row strip and the uncovered former maize row. After weighing, residues were evenly spread over their subplot, except for a 0.8 kg sample. The dry matter content of this sample was assessed by drying for 48 h at 70°C. N content was determined in the dried material after pooling samples from identical treatments. The carbon (C) content was assumed to be 400 g kg^{-1} dry matter (Thorup-Kristensen, 1994; Wyland *et al.*, 1995). Heights of intact cover crops and their stubbles after harvesting, were measured annually with a tempex disc (diameter 0.5 m, weight 0.345 kg; according to Keuning (1984)). The difference in height before and after harvesting was related to the observed N uptake. This relationship (26 kg N per 0.1 m for both cover crops, $P<0.001$) was used to estimate the N uptake in the stubble.

Dry matter yields of maize were determined by weighing the fresh material from the inner 12 m x 3 m area of each subplot. Dry matter content was determined by drying a subsample of 0.8 kg at 105°C for 48 h. Dried samples were pooled per treatment and analysed for total N.

Nitrate leaching was assumed to start after the soil was recharged to field capacity in autumn. Tensiometers were installed, groundwater levels were monitored and a pF curve was determined, to make an accurate estimate of the onset of the leaching season (Schröder *et al.*, 1992a). Nitrate leaching was calculated as the integral of the product of nitrate concentration and precipitation surplus over time. Nitrate concentrations were determined 4-10 times at regular intervals in samples of the soil solution derived from ceramic cups at 1 m depth in the first replicate of the experiment. Four cups per subplot (except the N3-rye and -grass plots) were installed.

Precipitation surplus was estimated as the difference between precipitation and evapotranspiration. The latter was set equal to 0.3 x potential evapotranspiration (ETo) for fallow and 0.9 x ETo for fully established cover crops (Schneider & Van Boheemen, 1986), a stage that was reached somewhat earlier for grass than for rye. ETo was calculated from data collected on a meteorological station in Twente at a distance of 50 km from Heino, whereas precipitation and temperature were recorded at a distance of 500 m from the experimental site.

6.3.5 Definitions

The apparent N mineralisation during summer (AMS, kg ha^{-1}), inclusive gains due to deposition and losses due to immobilisation, denitrification and leaching, was derived from balance sheet calculations accounting for the major mineral N inputs and outputs on N1 subplots:

AMS = (N uptake of maize + SMN at T2) - (SMN at T1 + fertiliser N) (1)

with T1 = April, before fertiliser and slurry application, and T2 = September

The apparent N mineralisation during winter on N1 subplots (AMW, kg ha^{-1}), inclusive gains due to deposition and losses due to immobilisation and denitrification, was defined as:

AMW = (N uptake in shoot and stubble of cover crop + SMN at T1) + (leached N) - (SMN at T2 in the previous year) (2)

Dry matter yield response data of maize were fitted to the sum of SMN at T1 (before fertiliser and slurry application), fertiliser N and NH_4-N in slurry with quadratic regression models. The economically optimum amounts of available N that may be calculated from this relationship will be discussed in a separate paper.

The apparent N recovery of slurry N in the maize crop (ANR_{slc},%) was defined as:

ANR_{slc} = 100 x (N uptake of maize on N2 subplot - N uptake of maize on N1 subplot) / (total N input from slurry) (3)

The apparent N recovery of slurry N in the soil and maize crop together (ANR_{slsc},%) was defined as:

ANR_{slsc} = 100 x (N uptake of maize on N2 subplot - N uptake of maize on N1 subplot + (SMN at T2 on N2 subplot - SMN at T1 on N2 subplot) - (SMN at T2 on N1 subplot - SMN at T1 on N1 subplot)) /(total N input from slurry) (4)

For the calculation of the apparent recoveries of broadcast fertiliser N, the differences between the N5 and N2 treatments were used instead.
The apparent recovery of cover crop N (ANR_{CC},%) was calculated as the difference in N uptake of a maize crop preceded by a cover crop at the lowest N rate ($NY_{N1,CC}$) and a maize crop preceded by fallow at the lowest N rate ($NY_{N1,FW}$) and expressed as a percentage of the aboveground N uptake of the cover crop (NYCC):

$$ANR_{CC} = 100 \times (NY_{N1,CC} - NY_{N1,FW}) / NYCC \quad (5)$$

The fertiliser value of a cover crop (FV, kg N ha^{-1}) was determined in three steps. First, the dry matter yield data of maize (preceded by fallow) were fit to the sum (SUMN, kg N ha^{-1}) of SMN at T1 (before fertiliser and slurry application), fertiliser N and NH_4-N in slurry, with a quadratic response function for each individual year. Subsequently, SUMN was solved from this function for the dry matter yield of a maize crop preceded by a cover crop at the lowest N rate ($DMY_{N1,CC}$, kg ha^{-1}), using the a, b and c coefficients obtained from the first step:

$$DMY_{N1,CC} = a \times (SUMN)^2 + b\,(SUMN) + c \quad (6a)$$

Finally, FV was calculated from:

$$SUMN = FV + \text{subsurface side dressed fertiliser N} + \text{SMN at T1 on a cover cropped N1 subplot} \quad (6b)$$

When the increase of the dry matter yield of maize (preceded by fallow) at rates larger than N2 was insufficient to yield a significant fit with a quadratic response function, a linear plus plateau response function was used for the calculation of FV instead. Such a function assumes a linear positive response between N1 and N2 only. The slope (S) of the response equals:

$$S = (DMY_{N2,FW} - DMY_{N1,FW}) / (NH_4\text{-N in slurry} + \text{SMN at T1 on fallow N2 subplot} - \text{SMN at T1 on fallow N1 subplot}) \quad (7a)$$

As the dry matter yields of maize preceded by a cover crop ($DMY_{N1,CC}$) were always lower than the dry matter yields of maize preceded by fallow at the N2 rate ($DMY_{N2,FW}$), the yield response can now be described as:

$$DMY_{N1,CC} = DMY_{N1,FW} + S * (\text{FV} + \text{SMN at T1 on cover cropped N1 subplot} - \text{SMN at T1 on fallow N1 subplot}) \qquad (7b)$$

from which FV can be solved.

The relative fertiliser value of a cover crop (RFV,%) was defined as the fertiliser value (FV) expressed as a percentage of the aboveground N uptake of the cover crop (NYCC):

$$RFV = 100 \times FV / NYCC \qquad (8)$$

6.3.6 Weather conditions

Average daily temperature during summer were relatively low in 1991 and considerably higher than average in 1992 and 1994. In the other years temperature was close to the long term average (Table 6.3). Precipitation during summer exceeded the long term average, especially in 1988, 1993 and 1994. Dry spells, lasting 4-6 weeks occurred in May 1989 and July-August 1991. Average daily temperature during winter was much higher during the first 4 years. The winters of 1990-1991 and 1993-1994 were relatively dry and wet, respectively.

6.4 Results

6.4.1 Cover crop N uptake and overwinter losses

Averaged over the first 5 winters, the amount of N taken up by the aboveground plant parts on former maize N1 plots, was 36 and 39 kg ha^{-1} for rye and grass, respectively. On maize plots that had been fertilised with cattle slurry and/or broadcast fertiliser N (N2-N5), rye and grass took up 46 kg

ha^{-1} on average, without consistent differences between cover crop species and N rates. During the winter of 1993-1994 rye failed completely due to excessive rainfall and only 7-9 kg N ha^{-1} was stored in grass. Variation in N uptake of cover crops among years (5 and 6 years for rye and grass, respectively) was positively ($P<0.01$) related to the temperature sum (threshold 5°C) between the sowing date (rye) or maize harvest date (grass) and the date of destruction of the cover crop (Figure 6.1), and hardly to the N rates on maize. If winter temperatures had been more close to the long term average, less N would have been taken up by the cover crops.
Estimated C to N ratios at the time of harvest ranged from 13 to 22 for rye and from 15 to 22 for grass, during the first 5 experimental years without

Table 6.3. Weather conditions recorded in Twente (temperature) and Heino (precipitation).

Year	Summer (April 1 - September 30)		Winter (October 1 - March 31)	
	Precipitation	Average daily temperature	Precipitation	Average daily temperature
	(mm)	(°C)	(mm)	(°C)
1988	467	13.9		
			352	6.7
1989	289	14.2		
			320	6.9
1990	361	13.7		
			298	5.2
1991	301	13.3		
			323	5.5
1992	402	14.8		
			387	5.0
1993	593	13.8		
			491	4.6
1994	460	14.4		
Long term av.*	386	13.8	365	4.9

* long term average 1961-1990

any effect from the N rates applied to maize. In the final year all grass cover crops had an estimated C to N ratio of 35.

Cover crops reduced leaching during winter substantially at all N rates, grass being more effective than rye (Figure 6.2). This reduction was related to the N storage in the cover crops rather than to their water consumption since the estimated downward water transport was on average 251 mm when plots were fallow and 216 mm when plots were cover cropped.

The storage of N in cover crops was not sufficient to absorb all residual SMN, as illustrated by the increase of leaching with N rates in both fallow and cover cropped plots. Balance sheet calculations of the apparent N mineralisation during winter (with leaching losses accounted for) on fallow N1 plots showed that the gains of SMN due to mineralisation and deposition matched or exceeded the losses due to denitrification and immobilisation in all winters (range 9-72 kg ha^{-1}). The apparent mineralisation (AMW) on cover cropped plots was lower than on corresponding fallow plots, as indicated by the negative difference of the apparent mineralisation on cover cropped plots and fallow plots (Table 6.4). It is not likely that this was caused by our disregard of SMN in the 0.6-1.0 m soil layer. Inclusion of the 0.6-1.0 m layer in our balances of fallow and grass covered N1 and N5 treatments (separate data not presented here), made clear that the negative difference of the AMW even became slightly larger in all years.

Table 6.4. Difference between the apparent N mineralisation (kg ha^{-1}) during winter (September-April) on cover cropped plots and on fallow plots.

Contrast	Code	Mineral N rate (kg ha^{-1})	Year: 1988	1989	1990	1991	1992	1993	Average 1988-1993
Rye-Fallow	N1	20	0	9	-30	-26	1	-17	-11 NS**
	N2	94*	14	31	-63	-28	-3	-12	-10 NS
	N5	214*	-118	-41	-303	-29	-24	-30	-91 (P<0.05)
Grass-Fallow	N1	20	16	-3	-33	-9	-12	-10	-9 NS
	N2	94*	6	-30	-89	-55	-20	6	-30 (P<0.05)
	N5	214*	-69	-160	-264	1	-6	-19	-86 (P<0.05)

* in 1988 and 1989 42 kg ha^{-1} more

** significance of difference with corresponding fallow treatment in pairwise t-test; NS = not significant

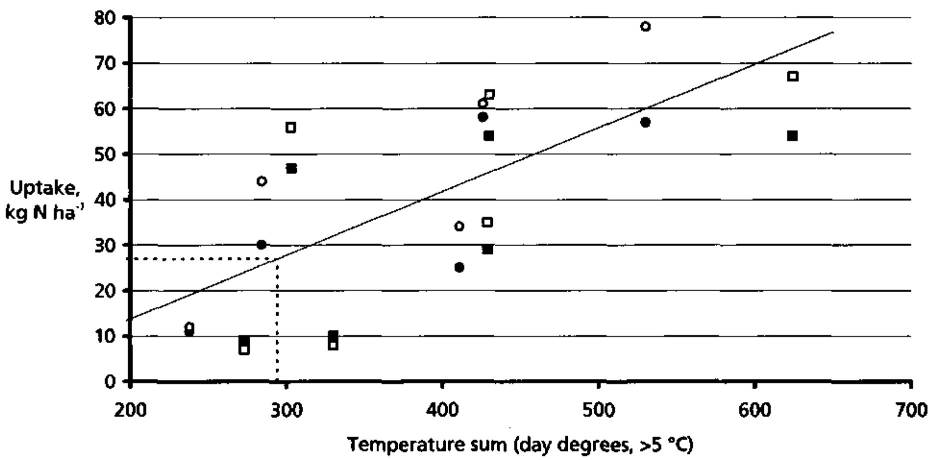


Figure 6.1. Aboveground N uptake of rye and grass (stubble included) in spring as affected by mineral N rates on a preceding maize crop (N1 = 20 kg mineral N ha^{-1} yr^{-1}, N2-N5 = 94-214 kg mineral N ha^{-1} yr^{-1}) and the temperature sum (threshold 5°C) between the dates of sowing (rye) or maize harvest (grass) and destruction in the subsequent spring (● = Rye N1, O = Rye N2-N5, ■ = Grass N1, □ = Grass N2-N5, ▪ : y = 0.14 x - 14.2, --- = Long term average: 1961-1990).

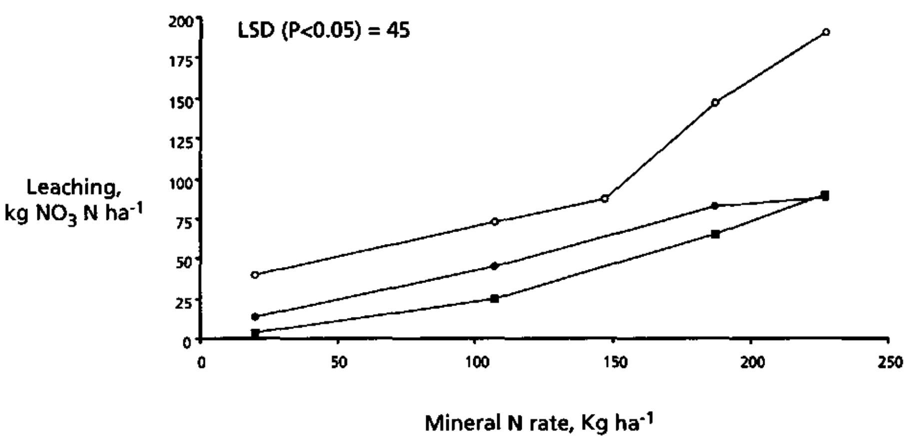


Figure 6.2. Relationship between the summed input of soil mineral N in spring (0.6 m layer), fertiliser N and NH_4-N in slurry applied to maize, and N leaching during winter (average from 1988-1989 to 1993-1994) as affected by cover crops (O = Fallow, ● = Rye, ■ = Grass).

Table 6.5. Dry matter yield of silage maize (t ha^{-1}) after winter fallow as affected by the mineral N rate (kg ha^{-1}) and the daily N mineralisation during summer (April-September) on N1-plots (kg ha^{-1} d^{-1}).

Code	Mineral N rate (kg ha^{-1})	Year: 1988	1989	1990	1991	1992	1993	1994	Average 1988-94
N1	20	14.94	13.61	11.87	8.16	11.07	10.09	10.04	11.40
N2	94*	15.24	16.96	14.13	12.21	15.68	14.51	15.82	14.94
N3	134*	15.39	17.28	14.20	12.44	16.98	15.13	15.35	15.25
N4	174*	15.49	17.50	13.52	12.69	17.26	14.74	16.08	15.33
N5	214*	14.99	16.50	14.01	12.24	16.23	15.01	15.77	14.96
LSD	(P<0.05)	1.30	1.21	1.37	1.51	1.75	1.03	1.10	0.613
Apparent N mineralisation	(kg ha^{-1} d^{-1})	1.11	0.75	0.53	0.43	0.59	0.39	0.37	0.60

* in 1988 and 1989 42 kg ha^{-1} more

6.4.2 Maize reponse to N

Dry matter yields of maize after winter fallow responded significantly to N in all years. In 1990 and 1994 no further increase of maize dry matter yields took place at rates larger than N2 (Table 6.5). The apparent mineralisation during summer showed a downward trend in time and the dry matter yields of N deficient (N1) maize reacted accordingly. Drought stress and low temperatures depressed yields at all N rates in 1991.

On average, 58% of the total N in cattle slurry was recovered in the soil and maize crop together, as calculated from the difference of balance sheets from N1 and N2 plots. Especially in later years, a larger fraction of the N in slurry was absorbed by the maize crop (Figure 6.3). Except for the drier years 1989 and 1991, much of the broadcast fertiliser N was lost during the growing season, as indicated by the difference of balance sheet calculations from N2 and N5 plots. On average, only 50% of the broadcast fertiliser N was recovered in the soil and maize crop together and only 7% was recovered in the maize crop (Figure 6.4).

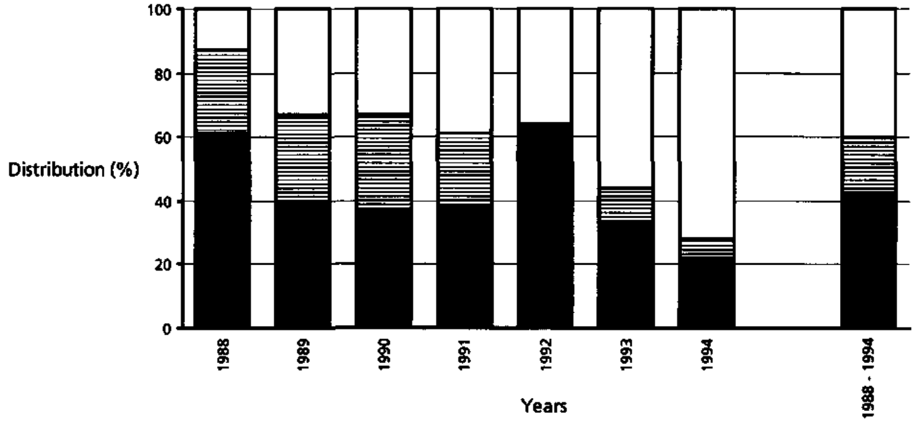


Figure 6.3. Recovery of total N in slurry (approximately 164 kg N ha^{-1}) in the maize crop and as soil mineral N after the harvest of maize (□ = in the crop, ⊟ = in the soil, ■ = not accounted for).

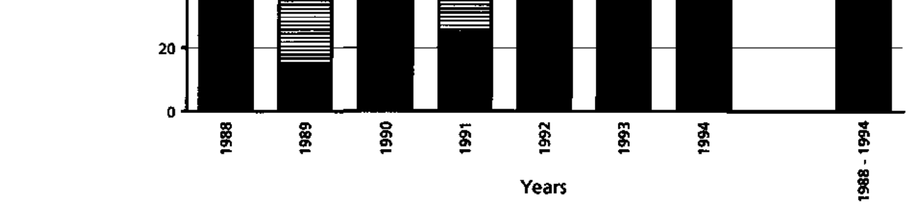


Figure 6.4. Recovery of broadcast fertiliser N (120 kg N ha^{-1}) applied in addition to subsurface side dressed fertiliser N (20 kg ha^{-1}) and slurry N (approximately 164 kg N ha^{-1}), in the maize crop and as soil mineral N after the harvest of maize (□= in the crop, ⊟ = in the soil, ■ = not accounted for).

Table 6.6. N uptake of silage maize (kg ha^{-1}) as affected by winter treatments and the mineral N rate (kg ha^{-1}).

Winter treatment	Code	Mineral N rate (kg ha^{-1})	Year: 1988	1989	1990	1991	1992	1993	1994	Average 1989-94
Fallow	N1	20	161	120	125	83	144	95	82	108 a**
	N2	94*	189	197	184	150	193	181	209	186 c
	N3	134*	194	192	185	156	207	194	209	191 c
	N4	174*	194	207	184	169	226	180	222	198 c
	N5	214*	180	206	174	155	245	194	210	197 c
Rye	N1	20	-	134	156	114	164	104	104	129 b
	N2	94*	-	208	194	152	201	189	224	195 c
Grass	N1	20	147	143	130	78	164	113	119	125 b
	N2	94*	167	206	182	141	217	174	213	189 c

* in 1988 and 1989 42 kg ha^{-1} more

** different letters denote significant differences (P<0.05) in F-test

6.4.3 Cover crop effects on maize yield

When N limited maize yields (especially on N1 and to a lesser extent on N2 plots), cover crop incorporation improved the availability of N significantly (P<0.05), as indicated by the increase of the N uptake in maize (Table 6.6). At higher N rates (N3-N5) rye cover crops had no effect on the N uptake and undersown grass even reduced dry matter yields of maize by 4%, 6%, and 5% (not significantly) in 1988, 1991 and 1993, respectively. Averaged over the complete experimental period, the yield depression associated with undersown grass amounted to 2%.

The N uptake of cover crops decreased in the course of the experiment, as winters happened to be colder in later years. The availability of N from cover crops to subsequent maize crops, however, increased over the years. In the last 2 years, in particular, the effect of cover crops on the N uptake of maize and residual N exceeded the aboveground N uptake of the cover crop itself (Figure 6.5). Even in 1994 when rye establisment had failed in the preceding autumn, the N uptake of maize on the former rye N1 subplot was 22 kg ha^{-1} larger than on the corresponding fallow plot.

Table 6.7. Fertiliser value of cover crops (FV, kg N ha^{-1}) and, in parentheses, their relative fertiliser value (RFV, expressed as a percentage of the aboveground N uptake of cover crop).

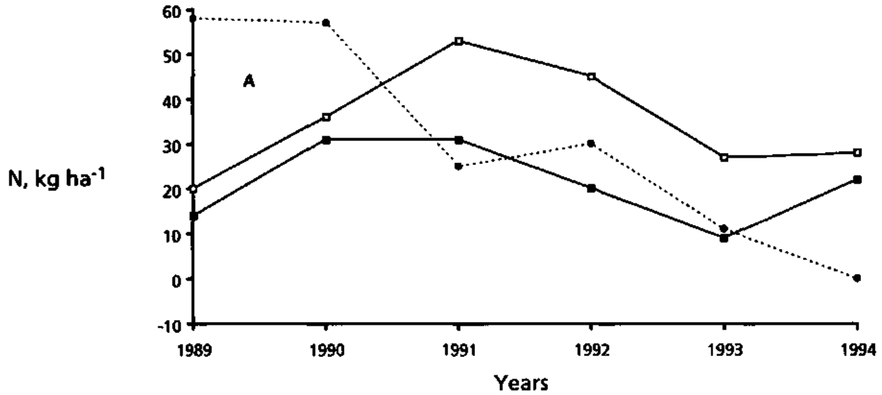
Winter treatment	Year:							
	1989	1990	1991	1992	1993	1994	1989-1993	1989-1994
Rye	25	94	25	25	21	29	38 (105)	37 (122)
Grass	31	19	-18	34	18	47	17 (44)	22 (65)

On average 115 and 73% of the aboveground rye N and grass N, respectively, were recovered in the soil and maize crop together, and 70% and 48% when evaluated by the recoveries in the maize crop only. Despite the decrease in the N uptake of cover crops, the fertiliser value (FV) remained fairly constant over the years (Table 6.7). The difference in the average fertiliser value of both cover crops in favour of rye, was mainly caused by the larger fertiliser value of rye in 1990 and 1991. In the other 3 years when both cover crops were grown, differences were negligible. The relative fertiliser value (RFV) increased from circa 50% in 1989 to circa 190% in 1993. Averaged over the whole period the relative fertiliser values were 122% and 65% for rye and grass, respectively.

Table 6.8. Linear regression models relating the residual soil mineral N in the upper 0.6 m soil layer (RSMN, kg ha^{-1}) after the harvest of silage maize (September) to the sum (SUMN, kg N ha^{-1}) of soil mineral N in the upper 0.6 m soil layer in spring (before fertiliser and slurry application), fertiliser N and NH_4-N in slurry and to the cumulative precipitation between May 1 and the date of autumn soil sampling (RAIN, mm): RSMN = a + (b x $SUMN^2$) + (c x RAIN).

Constant	Terms of the model:	
	$SUMN^2$	$SUMN^2$, RAIN
a	28.9*	123.6***
b	0.001444***	0.001271***
c		-0.2661**
Variance accounted for (%)	59	76

*, ** and *** denote significance at $P<0.05$, $P<0.01$ and $P<0.001$, respectively



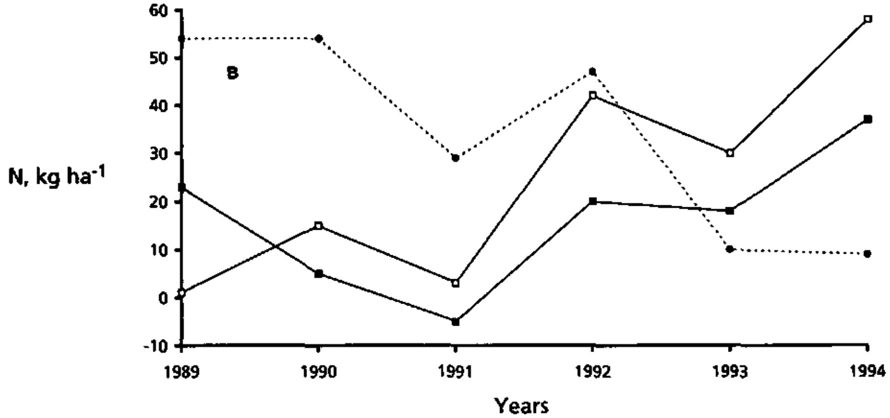


Figure 6.5. The N uptake of rye (A) and grass (B) in spring and the amount of N recovered in the maize crop only and as soil mineral N at the harvest and maize N (● = N in cover crop, ■ = N in maize crop, □ = N in the soil and maize crop together).

6.4.4 Residual soil mineral N

Residual SMN at T2 was positively related to N rates. The variance accounted for was increased by including summer rainfall into a multiple regression model. According to the model, a 100 mm increase of the summer rainfall reduces the residual SMN by about 27 kg ha^{-1} (Table 6.8). Residual SMN was

Table 6.9. Residual soil mineral N (kg ha^{-1}, 0.6 m) after the harvest of silage maize (September) as affected by winter treatments and the mineral N rate.

Winter treatment	N rate	Year: 1988	1989	1990	1991	1992	1993	1994	Average 1989-94
Fallow	20	55	39	48	49	23	19	38	36 ab**
	94*	113	116	116	88	28	33	39	70 bc
	214*	192	211	159	173	49	54	55	117 cd
Rye	20	-	41	55	49	29	25	32	39 ab
	94*	-	111	166	92	32	43	48	82 c
	214*	-	191	264	162	63	63	72	136 d
Grass	20	46	35	45	34	26	19	39	33 a
	94*	95	148	133	100	47	38	46	85 c
	214*	138	325	170	144	85	63	67	142 d

* in 1988 and 1989 42 kg ha^{-1} more

** different letters denote significant differences (P<0.05) in F-test

much larger in the earlier years of the experiment (Table 6.9). A significant increase of residual SMN on plots where cover crops had been incorporated, was not observed.

Variation in residual SMN was not reflected in the amount of SMN in the subsequent spring on fallow plots, indicating that the magnitude of N losses during the winter period, generally exceeded the potential N uptake of cover crops (Figure 6.6).

6.5 Discussion

6.5.1 Cover crop N uptake and overwinter losses

The aboveground N uptake of cover crops grown in combination with continous maize cropping, varied from 50-70 kg ha^{-1} in mild winters to less than 10 kg ha^{-1} in cold winters (Figure 6.1). This is considerably less than the N uptake of cover crops grown after cereals (Schröder *et al.*, 1997a). We estimate that under normal conditions, about 30 kg N ha^{-1} can be taken up by the aboveground plant parts of both rye and grass grown after maize. The larger uptake potential of grass due to its earlier establishment, was apparently offset by its initially stripwise presence between the maize rows and its greater sensitivity to low temperatures (Shipley *et al.*, 1992).

Differences in favour of grass might have become visible, however, if the N that was absorbed in roots had been included, as grass roots contain a larger amount of N than rye roots (Scott *et al.*, 1987). The uptake of N in cover crops was hardly affected by N application rates to maize although N rates had a distinct effect on residual SMN.

Cover crops reduced N leaching during winter by about 55% (Figure 6.2). Similar reductions were found by Martinez & Guiraud (1990). We estimated that cover crops reduced the precipitation surplus by 16% (35 mm). This is in agreement with changes of water discharge measured in lysimeter studies (Steffens & Vetter, 1984; Martinez & Guiraud, 1990). Hence, the 55% reduction of N leaching resulted from a reduced concentration of N in the soil solution rather than from a reduction of the discharged volume. The results indicated that the recovery of residual SMN by cover crops was incomplete. Consequently, nitrate leaching under cover cropped plots at high N rates, exceeded leaching under fallow plots at low N rates.

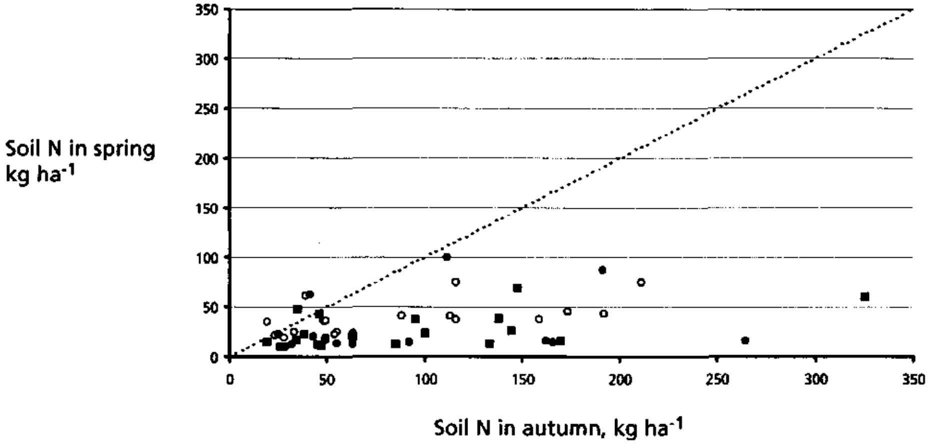


Figure 6.6. Relationship between soil mineral N (0.6 m layer) in the autumn and in the subsequent spring (O = Fallow, ● = Rye, ■ = Grass, --- : y = x).

Our findings suggest that the cropping techniques of maize should therefore aim at creating conditions in which cover crops are able to absorb the amount of residual SMN. Reduced N inputs and all measures that support an early cover crop establishment, can contribute to this.
Reduction of leaching as a result of cover cropping (Figure 6.2) exceeded the N uptake in the aboveground plant parts of the cover crops (Figure 6.5). This was also reflected by the lower overwinter apparent N mineralisation on covered plots (Table 6.4). On N1 plots the magnitude of this effect matched well with the estimated storage of N in roots of 5-15 kg ha^{-1}, based on combined data from Wellbank *et al.* (1974), Renius & Lütke Entrup (1985), Reeves *et al.* (1993) and Jackson *et al.* (1993). In general, the apparent N mineralisation on grass plots was lower than on rye plots. This may result from a larger N storage in grass roots than in rye roots (Scott *et al.*, 1987). Also, the apparent mineralisation may have been smaller on grass plots, as these plots were not tilled in autumn contrary to rye plots (Stokes *et al.*, 1992). Especially on N5 plots, however, the reduction of the apparent N mineralisation was large indicating that additional losses may have occurred under cover crops. Possibly, cover crops have stimulated denitrification due to their oxygen demand (Trolldenier, 1989; Scaglia *et al.*, 1985; Vos *et al.*, 1994) or promoted the immobilisation of N via carbohydrate exudation (Bottner *et al.*, 1984). This aspect deserves more attention in future research.

6.5.2 Maize reponse to N

Maize was responsive to N in all years. Calculations of the apparent N mineralisation during summer suggest that during the first few years, all plots still benefitted from heavy manure applications in the recent past (Tables 6.5).
Almost 60% of the N in spring injected cattle slurry was recovered in the crop-soil system (Figure 6.3). Especially during the last 4 years, the fraction absorbed by the crop was much larger than reported earlier for maize (Schröder & Dilz, 1987; Schröder *et al.*, 1993). This was probably due to the relatively low application rate, favourable weather conditions and a gradual decrease of the N supplying capacity of the soil.
On average, half of the broadcast fertiliser N applied in addition to cattle slurry and subsurface side dressed fertiliser N left the crop-soil system during the growing season. Only a very small fraction was absorbed by the crop

(Figure 6.4). Recoveries were negatively related to summer rainfall. Similar losses were reported by Jokela & Randall (1989) and Schröder *et al.* (1993).

6.5.3 Cover crop effects on maize yield

Results from our study indicated that only N deficient maize crops benefitted from the N provided via cover crop incorporation. In the first 2 years maize recovered 9-54% of the aboveground cover crop N. In the course of the years, however, recoveries gradually increased (Figure 6.5). This was probably partly due to the combined effects of factors improving the recovery of all sources of N in general, as discussed earlier. Moreover, the gradual increase of recoveries may point at an accumulation of residual effects of cover crops from previous years. Averaged over the 6 years 70% and 48% of the aboveground rye N and grass N, respectively, were recovered by subsequent maize crops. This superiority of rye over grass was also reported in a 2-year study of Thorup-Kristensen (1994) who found that barley recovered 43% and 17% of the N in rye and grass cover crops, respectively, when expressed as a percentage of their aboveground N uptake. When changes of SMN between spring and autumn were also accounted for, recoveries in our experiments increased to 115% and 73% for rye and grass, respectively. The N in grass cover crops, especially, may have decomposed too slowly to be fully at disposal of the maize, as average relative fertiliser values were 105% for rye and only 44% for grass (Table 6.7). Although rye and grass had similar C to N ratios in the aerial plant parts in our experiments, grass may decompose more slowly due to its larger root mass. The C to N ratio of roots of monocots is usually more than 40 (Reeves *et al.*, 1993). The observed relative fertiliser values for grass in the present study are slightly lower than the value of about 50% recently reported for fertilised grass ploughed down on clay soils in November (Schröder *et al.*, 1997a).

Contrary to our findings, Scott *et al.* (1987), Wagger (1989a, b) and Wyland *et al.* (1995) reported that cover crops had negative effects on subsequent crops. However, their cover crops had C to N ratios between 30 and 45 whereas it ranged from 10 to 30 in the relatively young cover crops in our experiment and that of Thorup-Kristensen (1994). As C to N ratios of cover crops are positively related to plant mass per unit area and, hence, N uptake (Scott *et al.*, 1987; Wagger, 1989a; Laurent & Mary, 1992; Bollero & Bullock, 1994), the reduction of leaching and the need for a timely destruction of the cover crop may be conflicting goals.

In most years, the effects of cover crops on maize yields could be fully understood by their positive effect on the availability of N. In 1988 and 1991, however, a negative effect of grass cover crops was observed at all N rates. As 1988 was a relatively wet year, competition for N rather than water is the most likely reason for it. Under the dry and cold weather conditions of 1991, undersown grass developed vigorously and competition for both N and water may have played a role. In the wet summer of 1993 grass had a negative effect on maize yields at larger N rates, only. The reason for this effect remained unclear.

The soil aggregates of the seedbed were more stable on plots where cover crops had been incorporated. Emergence and final plant density were not affected, however. After 6 years we could not detect any significant cover crop effect on the organic matter content of the soil (data not presented here).

6.5.4 Residual soil mineral N

Residual SMN was positively (P<0.01) related to N inputs (Table 6.8). Variance accounted for was improved when summer rainfall was included in the regression model (P<0.01). In a wet summer like 1993, the model predicted a 50 kg ha^{-1} decrease of residual SMN. According to the model, residual SMN resulting from the currently recommended SMN supply (early spring, 0.6 m) of 180 kg ha^{-1}, would be 61 kg N ha^{-1} under average summer rainfall conditions (390 mm). This is reasonably in line with the 54 kg N ha^{-1} that can be predicted from a similar model proposed by Schröder *et al.* (1993).

Residual SMN decreased in the course of the years (Table 6.9). This downward trend probably resulted from the combined effects of a reduction of the N rate from 1990 onwards, substantial losses of N in the summers of 1993 and 1994 and a gradual decrease of the N supplying capacity of the soil (Table 6.5).

Cover crops effects on residual SMN were insignificant. The N mineralised from cover crops in excess of the demand of maize, may well have been lost during the growing season, similarly to fertiliser N. This implies that cover crops may have postponed some of the losses from the winter to the summer season.

It should be noted that we assumed that the effective N inputs from slurry were equal to the ammoniacal N input. Consequently, gains due to the mineralisation of organic slurry N on the one hand and losses due to ammonia volatilisation on the other hand, were discounted. Therefore, coefficients of our models describing the response of residual N and maize yields (and the fertiliser values of cover crops deduced from them) to N inputs, could have been slightly different when mineral fertilisers had been the only N input.

In conclusion, cover crops grown after maize and incorporated in spring, reduced the overwinter leaching losses of SMN residues by about 55% over a broad range of N input levels. The fraction of the cover crop N that decomposed within the growing season appeared to increase in the course of the years. This was hardly reflected by an increase of residual SMN on plots where cover crops had been incorporated because mineralised N was either taken up by the present maize crop or already lost between early spring and late summer. Averaged over the 6 years of our experiment, the positive effect on the dry matter yield of N deficient maize was equivalent to the effect of a fertiliser N rate amounting to 105% and 44% of the aboveground N in rye and grass, respectively. As N released from overwintering cover crops will not be reflected in the amount of SMN in early spring, N recommendations for maize based on SMN measurements need a downward adjustment when cover crops are grown.

CHAPTER 7

MODELLING THE RESIDUAL N EFFECT OF SLURRY APPLIED TO MAIZE LAND ON DAIRY FARMS IN THE NETHERLANDS

J.J. Schröder and H. van Keulen

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7.1 Abstract

Quantification of the residual N effect of manuring is required to maximise the financial returns of farming systems and to avoid contamination of the environment. This is of special concern to maize land in The Netherlands, since it has been used for manure disposal during more than 25 years. The decomposition rate of soil organic N was estimated from data of a long-term field experiment and used in a simulation model. Subsequently, the model was used to estimate the effects of Dutch manuring practice on maize land. The time course of the nitrogen (N) mineralisation rate was estimated for three scenarios: i) following actual manure applications which have declined with time (A scenario); ii) assuming continuous applications in accordance with the present and anticipated legislation (P scenario); iii) assuming applications of 200 kg mineral fertiliser N ha^{-1} yr^{-1} only (M scenario).
We estimated that the actual mineralisation rate (following the A scenario) in 1995 was 23-31 kg N ha^{-1} yr^{-1} higher than when manure had been applied at moderate rates (following the P scenario). Corresponding estimates for the year 2005 still amounted to 18-19 kg N ha^{-1} yr^{-1}. Our calculations suggest that it may be difficult to maintain soil organic N pools with mineral fertiliser only. Consequently, the mineralisation rate following the M scenario decreased with time as did the yields of silage maize. The magnitude of the residual effect found in the present study, indicates that there is need and scope for fine tuning of N fertiliser recommendations. The simple model used in this paper seems a suitable tool to explore the magnitude of the residual effect of manuring.

Keywords: maize (*Zea mays* L.), manure, mineralisation, nitrogen, residual effect, simulation, slurry

7.2 Introduction

From the early seventies, the area of forage maize on Dutch sandy soils increased spectacularly at the expense of other forage crops including grass (Anonymous, 1971-1996). Maize is mostly grown continuously because of its tolerance to a high cropping frequency.

A more than proportional share of the manure production on Dutch sandy soils has been allocated to maize land for various reasons. One of the reasons is the insensitivity of the yield and quality of forage maize to heavy applications of manure (Schröder & Dilz, 1987).

Legislation on the timing and method of manure application was introduced in The Netherlands in 1987. In addition, upper boundaries were set to manure application rates. Legislation was initially extremely mild, especially for farmers growing maize, as, until recently, higher application rates were permitted on maize land than on all other arable land and grassland. The upper limits of the application rates on maize land were gradually reduced from circa 860 kg cattle slurry nitrogen (N) or 590 kg pig slurry-N ha^{-1} yr^{-1} in 1987 to circa 240 kg cattle slurry-N or 180 kg pig slurry-N ha^{-1} yr^{-1} in 1996 (Goossensen & Meeuwissen, 1990). Hence, permitted N inputs via slurries have exceeded the N uptake potential of maize for many years.

Manuring practices are reflected in higher nitrate concentrations in the upper groundwater under maize land than under grassland, as indicated by a survey in 1993 (Van Swinderen *et al.* ,1996). However, the N surplus is not fully lost from the system as N is partly stored in soil organic matter. This material is decomposed in time periods varying from months to decades (Lund & Doss, 1980; Magdoff & Amadon, 1980; Sommerfeldt *et al.*, 1988; Liang & Mackenzie, 1992). Sooner or later, organic matter will mineralise and pose a threat to the environment if the N release is disregarded in the nutrient management (Görlitz *et al.*, 1985; Werner *et al.*, 1985; Dilz *et al.*, 1990; Schröder *et al.*, 1997a). Therefore, accurate quantification of the residual N effect of manuring is needed to adjust fertiliser N inputs to crop requirements. Quantification is also indispensable for a correct interpretation of the short-term effects observed in experiments, in terms of the long-term consequences. Without such knowledge, fertiliser management strategies may lead to an undesired accumulation or depletion of nutrient reserves in the soil. Motavalli *et al.* (1992), for instance, showed that the N requirements of maize are strongly influenced by the N rates applied in previous years. It is very likely that this holds also for maize land in The Netherlands, given the excessive application of manure in the past. Experimental data on the N contribution from manure applied to maize land for more than 25 years, to crop N supply are not available. Hence, the magnitude of effects can only be explored via simulation studies. An example of such a study was recently reported by Whitmore & Schröder (1996). They used a relatively complex model describing carbon (C) transformations next to N transformations. The model requires a relatively extensive data input, including weather and soil data, which may limit its applicability. Wolf *et al.* (1989) developed a much simpler soil organic N model. The limited data requirement of their model makes it reasonably easy to find complete data sets for its validation, as illustrated by Wolf & Van Keulen (1989). The model also satisfactorily predicted the N requirements of maize, as observed in field experiments and appeared suitable to make long-term projections of the N requirements of tropical maize (Osmond *et al.*, 1992). We decided to test the suitability of this simple model of Wolf *et al.* (1989) to predict the N mineralisation in soils having received different amounts of manure for a large number of years. Subsequently, the model was used to evaluate the Dutch manuring practice on maize land of dairy farms, in terms of N mineralisation, N uptake and N losses.

7.3 Materials and methods

7.3.1 Experimental setup

The decomposition rate of manure, needed to run the model of Wolf *et al.* (1989), was estimated from data of a long-term experiment on a sandy soil in Maarheeze, the Netherlands, carried out from 1974-1983. In this experiment, cattle slurry was applied in all years but 1983, at rates ranging from 50 to 300 m^3 ha^{-1} yr^{-1}. The lowest slurry application rate was supplemented by 90 kg ha^{-1} yr^{-1} mineral fertiliser N from 1974 to 1979. Nutrient contents of the slurry were assessed at each application date and averaged 5.1 kg N, 1.0 kg phosphorus (P) and 4.6 kg potash (K) m^{-3} slurry. Slurry rates were registered, using a tractor-pulled precision applicator especially developed for field trials. Data on N inputs via atmospheric deposition were derived from Erisman & Heij (1991) and Bleeker *et al* (1994).

Silage maize was grown in the years 1974-1982 and its N uptake was assessed annually by measuring dry matter yields (total above-ground mass) and N (Kjeldahl) contents. Total soil N (Kjeldahl), soil mineral N (by extraction with 1 *N* KCl) and soil organic matter (by loss on ignition) contents were determined per treatment to a depth of 60 cm, in the autumns of 1975, 1981 and 1982. Total N contents were used to calculate the size of the N pool (kg ha^{-1}) by multiplying with a C-content dependent bulk density (Whitmore *et al.*, 1992) for which we assumed an average C-content of the organic matter of 0.45 kg kg^{-1}. Organic N was defined as the difference between total soil N and mineral soil N. Over-winter N leaching was calculated as the integral of the product of mineral N concentrations (measured with ceramic cups installed at 100 cm depth) and precipitation surplus, from 1977-1978 to 1981-1982.

In the last year of the experiment (1983), Italian ryegrass was grown on the total experimental area to determine the residual N effect of the slurry, with split mineral fertiliser N rates (0, 160, 320, 480 kg N ha^{-1}) superimposed on all former slurry treatments. Grass was planted on March 15 and cut five times during the season. N uptake in the grass was assessed at each harvest date. Details of the experiment are given in Schröder (1985a) and Schröder & Dilz (1987).

7.3.2 Model description

In their model, Wolf *et al.* (1989) distinguish a labile (LON) and a stable (SON) soil organic N pool. Inputs, such as mineral fertiliser (NFER), manure (NSLURRY) and deposition (NRAIN) are partitioned to crop uptake, aggregated losses (leaching, denitrification, volatilisation) and LON. SON is transferred to LON from which mineralised N is partitioned among crop uptake, losses and SON. We adopted a transfer coefficient from LON to SON of 0.15 and a ratio between the time constant of conversion of SON (TCS) and the time constant of conversion of LON (TCL) of 20 (Wolf *et al.*, 1989). This implies that in an equilibrium situation SON is 3 times larger than LON (viz.: 3 / 0.15 = 20). TCL is best derived from the crop N uptake of a control plot without fertiliser (Wolf *et al.*, 1989), as present in the Maarheeze experiment in 1983.

Table 7.2. Estimated actual slurry rates (m^3 ha^{-1} yr^{-1}) and N inputs with slurry and mineral fertiliser (kg N ha^{-1} yr^{-1}) on maize land of dairy farms (A scenario).

		Year							
		1970	1975	1980	1985	1990	1995	2000	2005
Slurry	Rate	50	50	74	74	50	50	50	50
	N input	220	220	326	326	230	240	245	245
Fertiliser	N input	200	192	133	30	73	68	65	45
TOTAL*	N input	420	412	459	356	303	308	310	290

* exclusive atmospheric N deposition

increase of the N/P ratio in cattle slurry from 5.6 in 1987 to 6.3 in 1996 (Anonymous, 1985; Beijer & Westhoek, 1996). For later years we adopted the value of 6.3.

We assumed that manure was supplemented by mineral fertiliser N. Estimates had to be made, as accurate records are lacking. We assumed that until 1975 routinely 200 kg fertiliser N ha^{-1} yr^{-1} was applied. Between 1976 and 1990 N available from manure was gradually taken into account in the N requirements and replaced part of the mineral fertiliser N input. We supposed that by 1990 55% of the total N input from manure was accounted

Table 7.3. Comparison of the estimated actual use of slurry (m^3 ha^{-1} yr^{-1}) and mineral fertiliser N (kg ha^{-1} yr^{-1}) inputs on maize land of dairy farms (A scenario) and the inputs recorded in surveys among maize growers ((n) =number of maize fields included in the survey).

Year	Estimated actual use		Survey			
	Slurry	Mineral-N	Slurry	Mineral-N	(n)	Source of survey
1977	117	147	77	122	(105)	Ten Hag (PAGV, 1996, pers. comm.)
1981	111	83	103	155	(104)	Anonymous (1981)
1982	109	68	114	117	(54)	Boer (1984)
1981-1989	93	-	79	-	(24)	Den Boer (NMI, 1996, pers. comm.)
1994	50	-	43	-	(10)	Den Boer (NMI, 1996, pers. comm.)
average	*96*	*99*	*83*	*131*		

for. However, information from local extension officers made us surmise that 30 kg starter fertiliser N ha^{-1} was applied anyhow, irrespective of the N input through manure. From 2002, calculated N rates exceeded the permitted N surplus (= input with manure and mineral fertiliser minus output with crop produce) according to the anticipated legislation. To comply with the legislation we reduced the mineral fertiliser N rate from 65 to 60 kg ha^{-1} for the 2002-2004 period and from 65 to 45 kg N ha^{-1} for the year 2005.

Table 7.2 summarises our estimates of the time course of manure and mineral fertiliser N application in steps of five years. Scattered information from occasional surveys among maize growers provides confidence in these estimates (Table 7.3).

7.3.4 Scenarios

The time course (1970-2005) of soil organic N and mineralised N on maize land were simulated for three scenarios: i) following the actual manure applications, as defined in the previous section (A scenario); ii) assuming not more than 39 kg manure-P ha^{-1} yr^{-1} having been applied in accordance with present and anticipated legislation (P scenario); iii) assuming applications of 200 kg mineral fertiliser N ha^{-1} yr^{-1} only (M scenario). The initial store of organic soil N was set to 6000 kg ha^{-1}.

N inputs via atmospheric deposition were derived from national data given by Erisman & Heij (1991) and Bleeker *et al.* (1994). Deposition estimates ranged from 38 kg ha^{-1} yr^{-1} in 1995 to 52 kg ha^{-1} yr^{-1} in 1984.

We used the transfer coefficients given in Table 7.1. In the course of time, manure management has changed to application in spring, followed by immediate incorporation, due to legislation and farmers' awareness of the environmental impact. To mimic this change in technology in the A scenario, we gradually increased the fractions transferred to the crop from 0.20 in 1979 to 0.30 in 1988 with an associated reduction in losses.

For the P scenario we adopted constant N and P concentrations in the manure (similar to the ones used from 1996 onwards in the A scenario) and used the transfer coefficients arrived at in 1988 in the A scenario, throughout the entire period.

The model was applied for the three scenarios. The difference between the A and P scenario serves as an indicator for the additional mineralisation resulting from excessive manure applications. The difference between the P and M scenario reflects mineralisation resulting from moderate use of manure. Additionally, the long-term consequences of the three scenarios for N uptake of maize and aggregated N losses are explored. For this part of our study we assumed that 180 kg N ha^{-1} yr^{-1} were taken up at most by a maize crop. This value is slightly lower than the uptakes commonly observed in field experiments. Such a downward correction was considered necessary by us when maize is grown under practical conditions. If the sum of N allocations to the crop exceeded 180 kg N ha^{-1} yr^{-1} , the excess was allocated to losses.

7.3.5 Sensitivity analysis

An upper and a lower value for TCL was used in our calculations of the organic N pool dynamics and mineralisation to determine its effect on the outcome of our study. In addition to this, we made an estimate of the relative contributions of the initial organic matter pool and of the additional pools originating from slurry-inputs and from mineral fertiliser inputs to the simulated N mineralisation. We also explored the effect of LON/SON ratio on the simulated N mineralisation by changing the ratio from 3 to 4.5 (Wolf *et al.*, 1989).

7.4 Results

7.4.1 Observed and calculated size of the soil N pool

Cumulative slurry applications to maize land increased the soil organic N pool in the Maarheeze experiment. A considerably smaller annual increase of the N pool was found when the calculated change from 1975 was based on the measurements made in 1981 than when it was based on the measurements made in 1982 (Figure 7.1). Because of this variation and inconsistencies of the response, we decided to base our further calculations on the estimated annual increase derived from regression analysis of the pooled data.

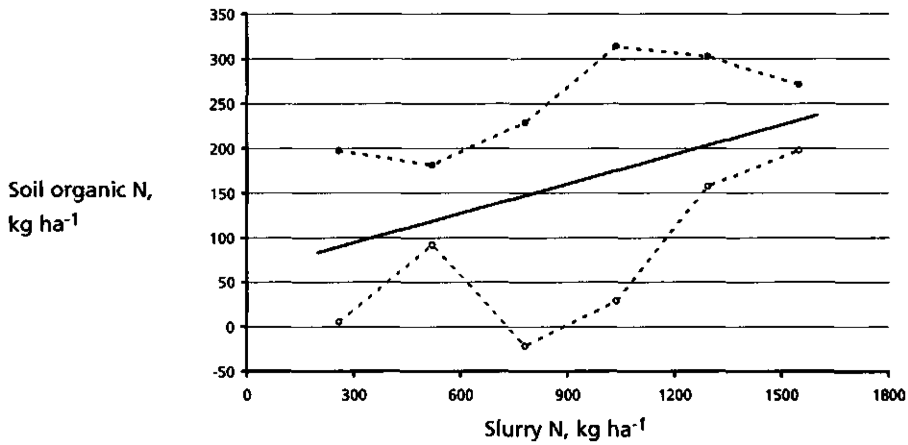

Figure 7.1. Average annual increase of soil organic N (kg $ha^{-1}yr^{-1}$) as related to annual N inputs with cattle slurry (kg $ha^{-1}yr^{-1}$) based on changes of the soil organic N pool between 1975 and 1981 (O) and on changes between 1975 and 1982 (●) and fitted annual increase of pooled data (—) after repeated cattle slurry applications on a sandy soil in Maarheeze continuously cropped with forage maize.

Only a part of the excess slurry N was stored in the soil, as indicated by balance sheet calculations of the N inputs and N outputs (Table 7.4). The surplus may indicate how much N was lost through volatilisation of NH_3-N and denitrification. N uptake of the grass grown in 1983, was positively related to the size of the N pool, as determined in the autumn of 1982 (Table 7.5). TCL's calculated according to equation 1, decreased from 38 yr in the 50 m^3 ha^{-1} treatment to 16 yr in the 300 m^3 ha^{-1} treatment, suggesting a higher decomposition rate when inputs were high. The calculated values of TCL for slurry rates corresponding to the rates of our scenarios, fall within the range of 20-45 yr found by Wolf & Van Keulen (1989) in the experiments used for the validation of their model. Hence, we decided to use TCL's of 20 and 40 yr in our scenario study.
The mean difference between the observed and simulated size of the organic N pool was not significantly different from zero (Table 7.6), suggesting that systematic errors were small. The variation around the Y = X line (Figure 7.2), however, was considerable. This does not necessarily point at inappropriateness of the model, as the assessment of the soil organic N supply was associated with errors also (Figure 7.1). Despite this mediocre goodness of fit between the observed and the simulated accumulation of soil organic N, we decided to proceed with the scenario study.

Table 7.4. Balance sheet of N inputs and outputs (kg ha^{-1} yr^{-1}) in the slurry experiment in Maarheeze (1976-1982).

		Slurry rate (m^3 ha^{-1} yr^{-1})					
		50	100	150	200	250	300
Inputs (I)	Slurry	258	519	781	1036	1292	1548
	Mineral fertiliser*	51	0	0	0	0	0
	Deposition	62	62	62	62	62	62
	TOTAL	371	581	843	1098	1354	1610
Outputs (O)	Crop uptake	137	159	177	199	195	198
	Leaching**	145	150	230	316	406	430
	Accumulation in soil***	89	118	147	175	203	231
	TOTAL	371	427	554	690	804	859
I - O	Surplus	0	154	289	408	550	751
	Aggregated losses****	145	304	519	724	956	1181

* 90 kg N ha^{-1} yr^{-1} in 1976-1979, 0 kg in other years

** not assessed in first and last winter

*** based on regression analysis (Figure 7.1)

**** leaching + surplus

Table 7.5. Soil organic N pool in the autumn of 1982 (kg ha^{-1}, 0-60 cm) following the application of different slurry amounts between 1972 and 1982, the N uptake (kg ha^{-1}) of unfertilised grass (5 cuts) in 1983 and the estimated time constant of conversion (TCL, yr) of the labile organic N pool (LON).

Slurry rate (m^3 ha^{-1} yr^{-1})	Organic N in soil (kg ha^{-1})	N uptake of grass (kg ha^{-1})	TCL (yr)
50	8786	78	38
100	8698	85	33
150	9310	110	24
200	10121	136	19
250	9213	151	15
300	9246	146	16

Table 7.6. Statistical indices for the goodness of fit between the observed and simulated size of the soil organic N pool (kg ha^{-1}, 0-60 cm) for time constants of conversion of the labile N pool (TCL) of 20 and 40 years.

	M[a]	SE_M [b]	r [c]	±500 [d]	±1000 [d]	Number of observations
TCL = 20 yr	47	234	0.48	33%	83%	12
TCL = 40 yr	-359	237	0.50	50%	67%	12

a Mean difference between observed and simulated values

b Standard error of the mean difference

c Correlation coefficient

d Simulations within ± 500 or ± 1000 kg N ha^{-1} of the corresponding observations

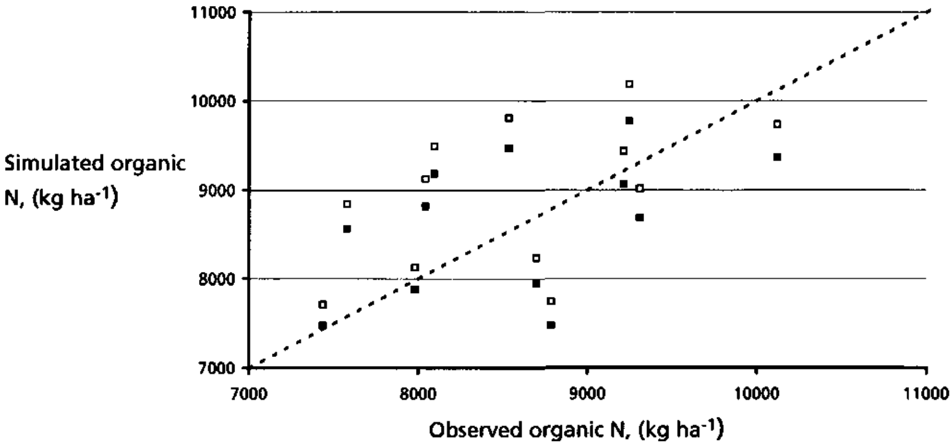

Figure 7.2. Observed versus simulated size of the soil organic N pool (kg ha^{-1}) after 6 (between 1975 and 1981) and 7 (between 1975 and 1982) annual applications of cattle slurry on a sandy soil continuously cropped with forage maize with a time constant of conversion of labile organic N (TCL) of 20 (■) and 40 (□) years. (---- = 'Y = X' line).

7.4.2 Scenarios

Model calculations with estimated data on actual N inputs indicate that the use of manure on maize land resulted in accumulation of soil organic N until about 1990 (Figure 7.3A, 7.3B). Obviously, accumulation was strongest when a low rate of decomposition was assumed, i.e. at a TCL of 40 yr. After 1995

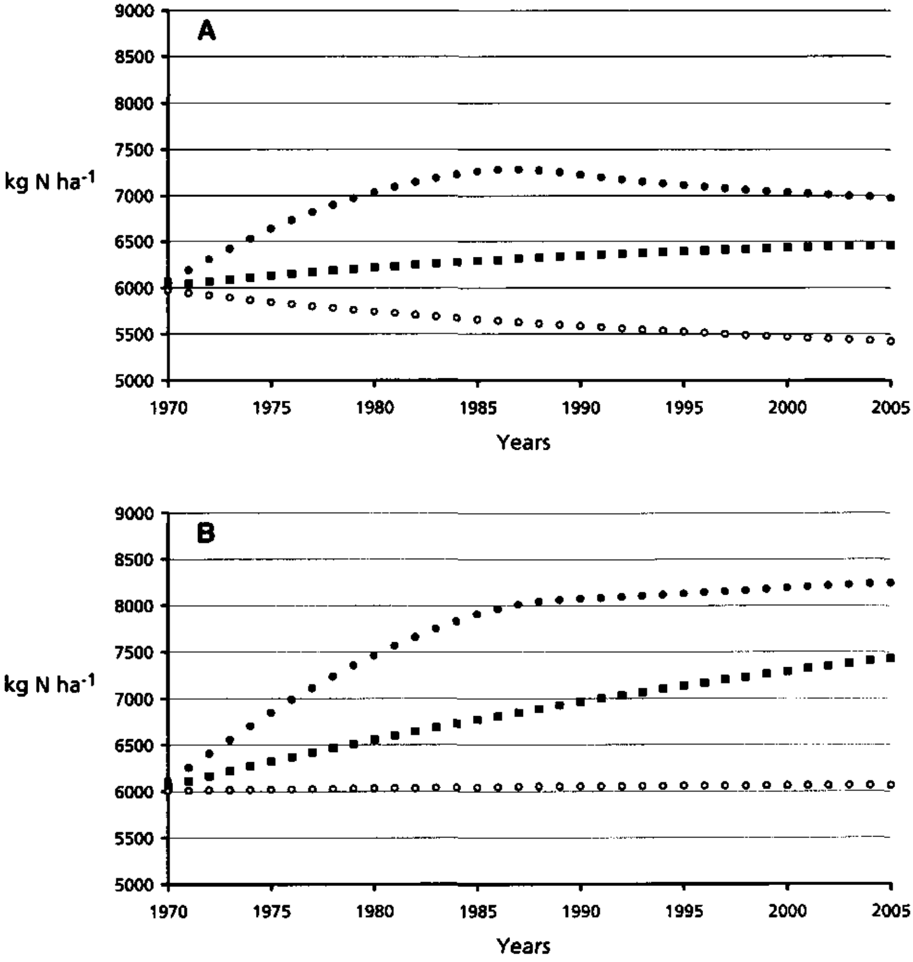

Figure 7.3. Size of the pool of soil organic N (kg ha^{-1}) on the maize land of dairy farms, with a time constant of conversion of labile organic N (TCL) of 20 (A) and 40 (B) years (● = actual use of manure, ■ = P-oriented use of manure, O = mineral N only).

the organic N pool increased slightly at a TCL of 40 yr, whereas it gradually decreased at a TCL of 20 yr. In the mineral fertiliser scenario, the organic N pool was about constant at a TCL of 40 yr, whereas a gradual depletion was calculated at a TCL of 20 yr. Since inputs of manure after 1996 are similar in the A and the P scenario, pool sizes of these two scenarios appear to converge towards values of about 7500 and 6500 kg ha^{-1} for TCL's of 40 and 20 yr, respectively.
The use of manure lead to a considerable increase in mineralisation rate which was largest at a TCL of 20 yr. The calculated difference in mineralisation rate among the various scenarios peaked around 1990 but persisted until the final years of our scenario study, especially at a TCL of 40 yr, as illustrated in Figure 7.4.
At a TCL of 20 yr, we calculated a difference in annual mineralisation rate between the A and the P scenario of 31 and 19 kg N ha^{-1} in 1995 and 2005, respectively (Table 7.7). The corresponding values for a TCL of 40 yr were 23 and 18 kg N ha^{-1}. If mineral fertilisers had been the only source of N (M scenario), 25-39 kg N ha^{-1} less would have mineralised annually compared to the P scenario in 1995. In 2005 the difference between the M and the P scenario had increased to 31-45 kg N ha^{-1}. The difference in mineralisation rate between the two extremes (A and M scenario) amounts to 48-70 kg N ha^{-1} in 1995 and 49-64 kg N ha^{-1} in 2005.

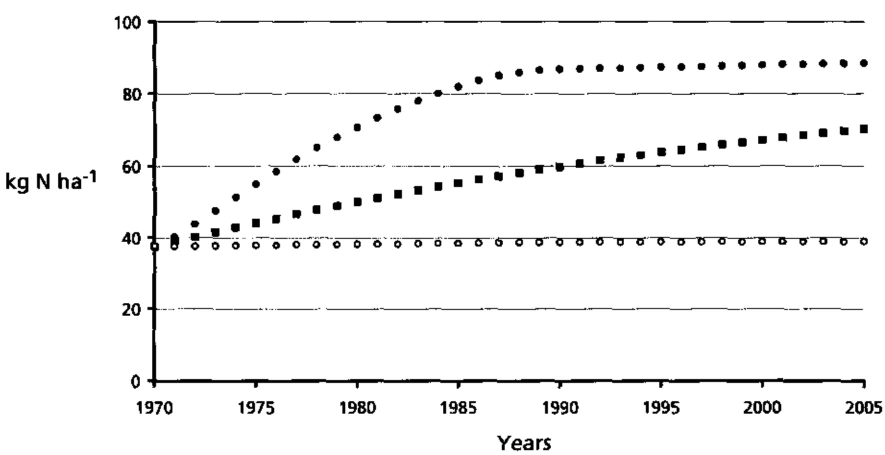

Figure 7.4. Annual mineralisation of soil organic N (kg ha^{-1}) on the maize land of dairy farms, with a time constant of conversion of labile organic N (TCL) of 40 years (● = actual use of manure, ■ = P-oriented use of manure, O = mineral N only).

Table 7.7. Simulated difference between the N mineralisation rate (kg ha^{-1} yr^{-1}) on actually manured maize land (A scenario) and on moderately manured maize land (P scenario) and between the N mineralisation rate on moderately manured maize land and on maize land where only mineral fertilisers were used (M scenario), as a function of the time constant of conversion (TCL, years).

Contrast	TCL	Year							
		1970	1975	1980	1985	1990	1995	2000	2005
A - P	20	0	30	37	45	41	31	24	19
	40	0	11	21	27	27	23	20	18
P - M	20	0	13	22	28	34	39	42	45
	40	0	6	12	17	21	25	29	31

As the size of the organic N pools in the A and P scenario will converge, so will calculated mineralisation rates. A continued moderate use of manure eventually resulted in an annual mineralisation rate of about 80 kg N ha^{-1} compared to about 40 kg N ha^{-1} when mineral fertilisers were the only source of N.

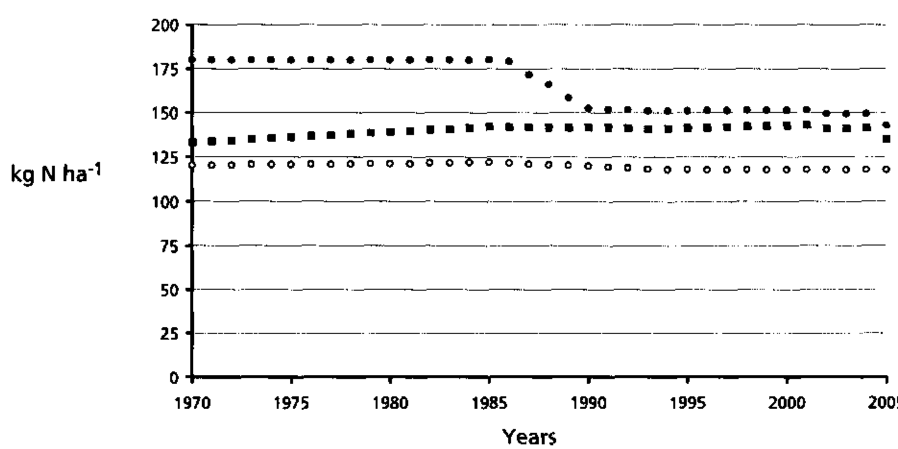

Figure 7.5. N uptake of maize (kg ha^{-1}) on the maize land of dairy farms, with a time constant of conversion of labile organic N (TCL) of 40 years (● = actual use of manure, ■ = P-oriented use of manure, O = mineral N only).

For the selected conditions application of 200 kg fertiliser-N ha^{-1} (M scenario) resulted in a N uptake of about 125 kg ha^{-1}. In both scenarios where manure was used, N uptake was higher, as illustrated for a TCL of 40 years in Figure 7.5. However, the predefined ceiling of the N uptake (180 kg N ha^{-1}) was only attained in the actual scenario (A scenario) in the 1975-1985 period.
Calculated N losses in the A scenario were largest between 1975 and 1985, as manure inputs increased during those years and fertiliser N inputs were insufficiently adjusted to manure inputs. Before the introduction of legislation in 1987, ammonia volatilisation contributed considerably to the losses, i.e. 23-49% of the difference in losses between the A and the M scenario was due to ammonia volatilisation. After 1987, volatilisation contributed only 15-19% to the difference in calculated losses. This is illustrated for a TCL of 40 years in Figure 7.6. In the long run, losses in the M scenario are about 50 kg N ha^{-1} yr^{-1} lower than in the scenarios where manure is used. This is mainly the result of the difference in size of the organic N pools and not because we assumed slightly larger losses from manure than from mineral fertiliser (Table 7.1). In 2005, the losses expressed per kg N uptake are about 0.2 kg smaller when mineral fertilisers are the only source of N (M scenario) than in the P scenario where manure

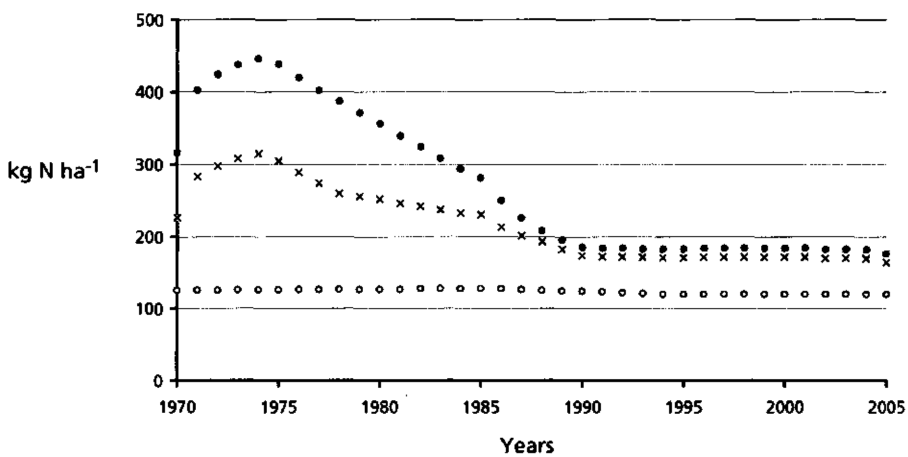

Figure 7.6. N loss (kg ha^{-1}) on the maize land of dairy farms, with a time constant of conversion of labile organic N (TCL) of 40 years (● = total loss inclusive NH_3-N loss with actual use of manure, **x** = total loss exclusive NH_3-N loss with actual use of manure, O = total loss with mineral fertiliser N only)

and mineral fertilisers are combined. The long-term difference in N uptake between the M and the P scenario is in the order of 20 kg ha^{-1}, implying that of the observed difference in N losses between these two scenarios, 4 kg N ha^{-1}, resulted from the nature of the N source. The remaining difference resulted from the difference in pool size.

7.4.3 Sensitivity analysis

The choice of the TCL value had a notable effect on the magnitude of the residual N effect at different moments in time (Table 7.7). The contribution of the slurry-input to the simulated mineralisation were much larger than the contribution from the initial soil organic matter pool or from the fertiliser-input (Table 7.8). This indicated that the calculated mineralisation rates are more strongly affected by assumptions concerning the actual application rates of manure than by assumptions concerning the initial pool size. Runs of the model (separate data not presented here) indicated that a change of the initial pool size by 1000 kg N ha^{-1}, changed the mineralisation rate by 3-4 kg N ha^{-1}, only. Changing the LON/SON ratio from 3 to 4.5 decreased the calculated mineralisation rates by 6 kg N ha^{-1}. Contrasts between the three scenarios were not affected, however.

Table 7.8. Estimated contribution of the initial organic matter pool and of the additional pools originating from slurry-inputs and from mineral fertiliser inputs to the simulated N mineralisation rate (kg ha^{-1} yr^{-1}) in 1995 on actually manured maize land (A scenario), on moderately manured maize land (P scenario) and on maize land where only mineral fertilisers were used (M scenario) with a TCL of 40 years and a LON/SON ratio of 3.

Contribution of:	Scenario:		
	A	P	M
Initial organic matter	23	23	23
Slurry-input	55	35	-
Fertiliser-input	7	5	14
Total	85	63	37

7.5 Discussion

Nitrogen in manure is generally not fully available in the year of application because the release of organically bound N takes time. Continued use of manure will result in a gradual increase in the organic matter pool until, after many years, the annual build-up of organic matter is in equilibrium with the annual decomposition. On the other hand, refraining from organic inputs may lead to a reduction in the organic matter pool. This may ultimately lower soil fertility. Knowledge of the relevant processes is needed for the fine tuning of fertiliser recommendations and for a proper evaluation of the long-term effects of nutrient management strategies, as depletion and accumulation may have undesired effects on crop production and environment.

Residual N effects, as observed in a field experiment in which cattle slurry was applied at various rates for 9 consecutive years, were used to calibrate a model developed by Wolf *et al.* (1989). The difference between the N inputs in the various treatments of this field experiment and the corresponding outputs, including N leaching and build-up of organic N, indicated how much N was lost through volatilisation and denitrification. Only at the 50 m^3 slurry ha^{-1} yr^{-1} treatment, the surplus was nil, suggesting no other N losses than leaching. This seems unrealistic, so we may have underestimated one of the N inputs or overestimated one of the N outputs.

The N uptake of an unfertilised grass crop, as observed in 1983, was positively related to build-up of organic N after application of cattle slurry in the previous 9 years. As on sandy soils residual mineral N in autumn is lost completely over-winter, except for an amount of circa 40 kg N ha^{-1} commonly present in spring in the upper 60 cm (Schröder *et al.*, 1996b), and winter rainfall between October 1982 and mid-March 1983 was 425 mm, we hypothesise that the observed difference in N uptake largely resulted from mineralised N. The estimated time constants of conversion were 20-40 yr for the labile soil organic N pool (LON). This is equivalent to relative decomposition rates of 2.5% - 5% yr^{-1} (viz.: 1 / 40 - 1 / 20) of LON. These values are within the range found by Wolf & Van Keulen (1989) in long-term experiments. When related to the total organic N pool (LON + SON), decomposition rates amounted to 0.7% - 1.4%. The order of magnitude is in reasonable agreement with the findings of Kortleven (1963) who concluded

that each year, 1.5% - 2% of the 'active' humus (i.e. exclusive the inert fraction) decomposes.
The observed residual N effect in the experiment that we used to estimate the decomposition rate of the soil organic N, is in fair agreement with the findings of Görlitz *et al.* (1985) and Dilz *et al.* (1990). From data reported by Görlitz *et al.* (1985) a residual effect equivalent to 2-4% of the annual N input with slurry after 4 years of application can be calculated as compared to 7% of the annual N input with slurry after 9 years of application in our experiment. Dilz *et al.* (1990) found a residual effect equivalent to 12-16% of the annual N input with farmyard manure after 11 years of application. The agreement between their results and ours becomes better when the residual effect is expressed as a percentage of the annual input of the resistant organic N ('Nr'), as defined by Sluijsmans & Kolenbrander (1977). The relative share of 'Nr' in farmyard manure and slurry is about 40% and 25%, respectively. Thus, we calculated a residual effect of 28% of the annual 'Nr' input in our experiment. The corresponding value in the experiment of Dilz *et al.* (1990) varied between 27% and 36%.
The results of our model are in good agreement with a simulation study by Whitmore & Schröder (1996). For the year 2005, they calculated a difference in mineralisation rate between their A and M scenario of 55-60 N ha^{-1}. The corresponding value in the present study was 49-64 kg N ha^{-1}. It must be noted, however, that slightly different assumptions were used in the definition of the scenarios in both model studies. Averaged over the 1975-1995 period Whitmore & Schröder (1996) assumed slurry-N and mineral fertiliser-N inputs of 310 and 170 kg ha^{-1} yr^{-1} in their A scenario. Corresponding values in the present study were 400 and 90 kg ha^{-1} yr^{-1}. The analysis presented in Table 7.8 pointed out that estimates of the mineralisation rate are notably affected by assumptions concerning the actual use of slurry and mineral fertiliser N.
The results of our scenario study indicate that maize fertilised at recommended rates, takes up considerably less N than the commonly observed amount of circa 180 kg N ha^{-1}. This means that maize production in our scenarios is often N limited, especially when mineral fertiliser is the only source of N. The discrepancy between this outcome of our modelling and the utter confidence of farmers in todays recommendations indicates that we may have been too pessimistic in our assumptions with respect to the effective contribution of atmospheric deposition, fertiliser or mineralisation

to crop uptake. However, the discrepancy may also reflect the need to better account for residual effects of N sources applied in previous years. After all, N recommendations are usually based on trials that have been carried out at fields that were amply manured in the years prior to experimentation. The simple model used in this paper seems a suitable tool to explore the magnitude of the associated residual effect.

CHAPTER 8

EFFECTS OF N APPLICATION ON AGRONOMIC AND ENVIRONMENTAL PARAMETERS IN SILAGE MAIZE PRODUCTION ON SANDY SOILS

J.J. Schröder, J.J. Neeteson, J.C.M. Withagen and I.G.A.M. Noij

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8.1 Abstract

The current nitrogen (N) use in silage maize production in The Netherlands leads to considerable N losses to the environment. Maize growers fear that a reduction of N inputs needed to minimise N losses might depress yields. The objective of this study was therefore to quantify: *1)* the response of silage maize dry matter (DM) yields to N, *2)* the economically optimal N reserve, and *3)* the trade-off between silage maize DM yield and N losses. The indicators of N losses used in this study were the difference between N input and N uptake and the post-harvest residual soil mineral N.

Regression models were used to fit DM yields and N uptakes of silage maize measured in 25 experiments on sandy soils in The Netherlands to the sum (SUMN) of the soil mineral N reserve (SMN_{early}) in March-April, plus mineral N in fertiliser, plus ammonium N in spring-applied slurry.

The values obtained for the economically optimal SUMN in the upper 30 and 60 cm of soil were respectively 173 and 195 kg N ha^{-1} (both with standard errors of 15 kg N ha^{-1}). The economically optimal SUMN was not significantly related to the attainable DM yield.

The DM yield and N uptake were also fitted to the measured soil mineral N reserve (SMN_{late}) in May-June which was determined in 10 of the experiments. The values obtained for the economically optimal SMN_{late} amounted to 147 and 229 kg N ha^{-1} (standard errors of 14 and 15 kg N ha^{-1}, respectively) for sampling depths of 30 and 60 cm, respectively.

The apparent N recovery (ANR) of maize averaged 53% at the economically optimal SUMN. The ANR rose considerably, however, when N was applied at lower rates, indicating that N losses may be considerably smaller in less intensive maize cropping. When maize was fertilised at 100 kg N ha^{-1} below the economic optimum, the ANR was 73%, the difference between the mineral N input and the N crop uptake decreased by 57 kg N ha^{-1} and the soil mineral N residue at the end of the growing season (0-60 cm) decreased by 24 kg N ha^{-1}. The associated reduction in DM yield averaged 16%.

It is concluded that adjusting the N input to a level below the economically optimal rate can reduce the risks for N losses to the environment associated with conventional maize production, with a limited effect on silage yields.

Keywords: maize, nitrogen, residual nitrogen, response model, slurry, soil sampling

8.2 Introduction

Two of the factors determining the economically optimal rate of fertiliser N are the demand for nitrogen (N) of a crop and its ability to take up N from the soil. Fertiliser requirements also depend on the amount of N available from sources other than fertiliser and, hence, the profitability of N fertiliser use can be improved by adjusting fertiliser N inputs to the amounts present in the soil at the start of the growing season (Wehrmann & Scharpf, 1986; Neeteson, 1989a). Recommendations based on this principle have been developed for maize, mainly in North America (Magdoff *et al.*, 1984; Fox *et al.*, 1989; Beauchamp & Kachanoski, 1989; Blackmer *et al.*, 1989; Magdoff, 1991; Binford *et al.*, 1992a; Klausner *et al.*, 1993; Schmitt & Randall, 1994; Vanotti & Bundy, 1994b), but hardly in Europe (Bassel *et al.*, 1987; Walther & Jäggli, 1989).

Nowadays, the environmental impact of fertiliser use deserves ample attention in addition to the financial rationale. To date, the pollution arising from the use of N has not been penalised financially in The Netherlands, except when farmers use fertilisers and manures excessively (Oenema *et al.*, 1997). Various indicators of the environmental impact of N use have been proposed, such as the fertiliser N recovery value, the difference between the N input and the N removed with crop products, and the post-harvest residual soil mineral N.

The agronomic and environmental objectives for maize are not always compatible. Only circa 50% of the mineral fertiliser is exploited by the crop (Osmond *et al.*, 1992) when maize is fertilised at an economically optimal N rate and a considerable amount of residual soil mineral N can be found after harvest (Ruselle *et al.*, 1981; Jokela & Randall, 1989; Jokela, 1992a; Lorenz, 1992; Aufhammer *et al.*, 1996). This discrepancy between N input that agronomists recommend and the input level that is environmentally acceptable, has been attributed to various factors: the uneven distribution of roots and of soil fertility, shallow rooting crops not exploiting the deeper reserves of nutrients, and the crop's physiological stage at harvest (Neeteson *et al.*, 1987; Greenwood *et al.*, 1989; Van Noordwijk & Wadman, 1992; De Willigen *et al.*, 1992; Neeteson, 1994). Results from field experiments on sandy soils in The Netherlands indicate that, when fertilised at a rate of 150 kg mineral N ha^{-1}, as much as 50-100 kg mineral N ha^{-1} may remain in the upper 60 cm of soil after the maize harvest (Schröder *et al.*, 1993; Schröder et *al.*, 1996b; Schröder & Ten Holte, 1996; Schröder, 1997). Under Northwest European conditions, this residual soil mineral N may easily leach out during winter, causing groundwater to exceed the nitrate threshold for drinking water laid down in the EU Nitrate Directive (Anonymous, 1980). This implies that the only way to reconcile the conventional method of growing maize with environmental objectives, is to apply economically sub-optimal N rates or to change the cropping techniques. As the latter option can be expensive, it should be preceded by an accurate quantification of the trade-off between conflicting goals. The present paper aims to do this. It describes research to quantify the trade-off between silage maize dry matter (DM) yield and potential N losses, using published data from field experiments. The following issues were addressed from that perspective:

- quantification of the relationships between the mineral N reserve including the soil mineral N present at the start of the growing season, the DM yield and N uptake of silage maize, the N surplus and post-harvest residual soil mineral N,
- determination of the economically optimal mineral N reserve,
- determination of the loss of yield when a sub-optimal N application rate is required for environmental reasons.

8.3 Materials and methods

8.3.1 Origin of data

The study was based on data on the response of silage maize DM yields and N uptakes to applied N, collected in The Netherlands in 25 field experiments. All experiments were carried out on sandy soils where maize was grown continuously or in rotation with other arable crops, except for Experiment 17 where maize was preceded by permanent grassland. Treatments consisted of combinations of mineral fertiliser N and cattle slurry. Each experiment included at least five treatments. Table 8.1 summarises some aspects of the experiments. For details on the experimental design, soil characteristics, husbandry techniques, observations, measurements and weather conditions, see Schröder *et al.* (1993), Schröder *et al.* (1996b), Schröder & Ten Holte (1996) and Schröder (1997) for the Experiments 1-8, 9-15, 16-17 and 18-25, respectively.

Table 8.1. Additional information on experiments and sites

Experiment number	Year (n)	Location	Reference[1]	Organic matter content[2]	Previous crop in: year n-1	Previous crop in: year n-2	Winter cover crop	Manuring history[3]	Input range (kg N ha^{-1}): slurry	Input range (kg N ha^{-1}): mineral fertiliser	Number of treatments: slurry	Number of treatments: mineral fertiliser	Number of treatments: combinations used[4]
1	1982	Wageningen	1, a	3.5	barley	maize	no	regularly	0-335	0-200	6	3	14
2	1983	Wageningen	1, b	3.5	barley	beets	no	regularly	0-570	0-200	8	4	27
3	1984	Wageningen	1, c	3.4	barley	beets	no	regularly	0-237	0-200	16	4	64
4	1985	Wageningen	1, d	3.5	beets	wheat	no	regularly	0-439	0-200	11	4	38
5	1986	Wageningen	1, e	3.6	potatoes	barley	no	regularly	0-354	0-160	18	2	21
6	1987	Wageningen	1, e	3.4	maize	potatoes	no	regularly	0-552	0-160	18	2	21
7 - 8	1988-89	Wageningen	1, e	3.3	maize	maize	no	regularly	0-553	0-160	18	2	21
9 - 15	1988-94	Heino	2, fallow	3.0	maize	maize	no	annually	0-225	20-140	2	4	5
16	1990	Hengelo	3, lot 22	4.3	maize	maize	yes	annually	0	0-200	1	5	5
17	1991	Hengelo	3, lot 5	4.7	grass	grass	yes	annually	66	0-160	1	5	5
18	1983	Heeten	4, A	-	maize	maize	no	annually	0-388	0-150	3	4	8
19	1983	Westerhoven	4, B	2.7	maize	maize	no	annually	0-338	0-150	3	4	8
20 - 21	1986-87	Hulsen	4, C	6.7	maize	maize	no	annually	0-333	0-200	3	3	7
22	1985	Creil	4, D	1.7	gladiolus	wheat	no	rarely	153	0-160	1	5	5
23 - 24	1986-87	Budel	4, E	3.3	maize	maize	no	annually	169	0-160	1	5	5
25	1987	Zuidwolde	4, F	6.8	maize	maize	no	annually	127	0-160	1	5	5

1 Indices 1, 2, 3 and 4 refer to Schöder *et al.* (1993), Schröder *et al.* (1996b), Schröder & Ten Holte (1996) and Schröder (1997), respectively. The second index refers to the nomination of site-years in the original publications.

2 In upper 25 cm, %.

3 Annually, regularly, rarely: manure applications once every year, once every second or third year, once every fourth or fifth year at most, respectively

4 The number of combinations of slurry and mineral fertiliser N rates used in the regression analysis is not always equal to the product of the numbers of slurry and mineral fertiliser N rates because not all combinations were included in the experiments (Experiments 9-15, 18-21) or because SUMN60 inputs exceeding 350 kg N ha^{-1} were excluded from the analysis (Experiments 1, 2 and 4).

8.3.2 Analysis of the data

DM yield and N uptake data recorded at silage maturity stage (approximately 30% DM content) were fitted to the sum of the soil mineral N reserve (including nitrate N and ammonium N) in either the top 30 cm ($SMN_{early,30}$; kg N ha^{-1}) or the top 60 cm ($SMN_{early,60}$; kg N ha^{-1}) in spring (before fertiliser and slurry application), plus the fertiliser N, plus the NH_4-N in spring-applied slurry. This sum of N terms was denoted $SUMN_{30}$ (kg ha^{-1}) when it included $SMN_{early,30}$, and $SUMN_{60}$ (kg ha^{-1}) when it included $SMN_{early,60}$.

In 10 of the 25 experiments, a sufficient number of additional late soil samplings was available to enable the silage maize DM yields to be fitted to the SMN reserve in the top 30 cm or 60 cm circa 4 weeks after emergence ($SMN_{late,30}$ and $SMN_{late,60}$, respectively; kg N ha^{-1}).

We used different response models: a quadratic plus plateau model (QP model, Equation 1), a negative exponential model (EX model, Equation 2) and a quadratic model (Q model, Equation 3). For the regression analysis of the N uptake we also used a linear model (L model, Equation 4) and a linear plus plateau model (LP model, Equation 5).

QP model:

$$Y = Ymax - a * (k-X)^2 \quad \text{if } X < k \text{ and} \qquad (1a),$$

$$Y = Ymax \quad \text{if } X >= k \qquad (1b),$$

EX model:

$$Y = Ymax + a * (r^X) \qquad (2),$$

Q model

$$Y = a * X^2 + b * X + c \qquad (3),$$

L model

$$Y = a * X + c \qquad (4),$$

LP model:

$$Y = Ymax - a * (k-X) \quad \text{if } X < k \text{ and} \qquad (5a),$$

$$Y = Ymax \quad \text{if } X >= k \qquad (5b),$$

with Y representing the DM yield or N uptake and X representing $SUMN_{30}$, $SUMN_{60}$, $SMN_{late,30}$ or $SMN_{late,60}$.

The adjusted correlation coefficient of the regression (Montgomery & Peck, 1982) was used as a measure of the variance accounted for (VAF) by each model. When models performed equally well in terms of the VAF, we selected the model with the most significant coefficients. When these criteria could not help in selecting the most appropriate model, the model that predicted the lowest value for the economically optimal N reserve was chosen. The economically optimal N reserve was defined as the reserve at which adding one more kg N yielded less than 5 kg additional silage DM. Mathematically this was done by setting the first derivative of the analytical relationship equal to the ratio of the costs of N fertiliser and price of silage i.e. 5 kg silage DM per kg N.

The apparent N recovery (ANR, %) of the mineral N inputs was defined as the difference between the fitted N uptake (exclusive N in roots and stubble) of a fertilised crop and the fitted N uptake of an unfertilised crop (with no other input than $SMN_{early,60}$), expressed as a percentage of the mineral N input (Equation 6). ANR's were calculated for the mineral N input from fertiliser and slurry (i.e. without $SMN_{early,60}$) at the economically optimal N reserve and for a sub-optimal N reserve.

ANR = ((N uptake of a maize crop receiving mineral fertiliser N and/or slurry N)

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(N uptake of an unfertilised maize crop))

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($SUMN - SMN_{early,\ 60}$) (6).

The N surplus per unit area was defined as the difference between the N input and the N uptake in the crop. Two types of surplus were defined: $NSURMIN_{ha}$ (kg N ha^{-1}) referring to the input in terms of mineral N (from either mineral fertiliser or slurry) and $NSURTOT_{ha}$ (kg N ha^{-1}) referring to the input in terms of total N (when slurry is the only source of N). The ANR and $NSURMIN_{ha}$ were calculated for each individual experiment before averaging. $NSURTOT_{ha}$ was calculated after averaging, assuming that the mineral N : organic N ratio in slurry equals 1 (Beijer & Westhoek, 1996).

Post-harvest residual soil mineral N in the upper 60 cm ($RSMN_{60}$, kg ha^{-1}) was assessed in a limited number of treatments in each experiment. Regression analysis between $RSMN_{60}$ and $SUMN_{60}$ was performed on the pooled data, using a quadratic model which described the response better (in terms of the adjusted correlation coefficient) than a quadratic plus plateau model, a linear plus plateau model, an exponential model or a linear plus linear ('broken stick') model. Contrary to the results of the regression analysis per group of experiments (Schröder *et al.*, 1993; Schröder *et al.*, 1996b; Schröder & Ten Holte, 1996; Schröder, 1997), inclusion of the N uptake did not improve the performance of the model, which is why in this paper the N uptake has not been used as an explanatory variable for RSMN.

8.4 Results

8.4.1 Response models

A diminishing response of the DM yield to $SUMN_{30}$ and $SUMN_{60}$ was observed in all 25 experiments. This response could be described significantly (*P*<0.05 for all three coefficients in 18 of the 25 experiments, 0.05<*P*<0.10 in the remaining 7 experiments) by at least one of the models described by Equations 1-3. All three models significantly fitted DM yields to $SUMN_{60}$ in 6 experiments and DM yields to $SUMN_{30}$ in 9 experiments (Table 8.2). With few exceptions, the QP and EX models had slightly larger VAF's than the Q model. The economically optimal reserve decreased in the order Q > EX > QP. The Q model tended to overestimate the observed DM yields around the calculated optimal $SUMN_{30}$ (arbitrarily chosen to range from minus 50 to plus 50 kg N ha^{-1} around the optimal $SUMN_{30}$) by 0.105 t DM ha^{-1}, on average. The actual slope of the response curve will therefore have been more gentle than the predicted one and the profitability of N applications may thus have been overestimated with the Q model. The corresponding difference between predicted and observed DM yields was -0.020 for the EX model and -0.015 t DM ha^{-1} for the QP model.

8.4.2 Optimal N reserve at early sampling date

At a price ratio of 5, the economically optimal reserve at the early sampling stage (SUMN) averaged 173 and 195 kg N ha^{-1} for sampling depths of 30 cm and 60 cm, respectively (Table 8.3). Doubling the cost of fertiliser N would

Table 8.2. Effect of regression models on the economically optimal N reserve for silage maize at an early sampling stage ($SUMN_{opt,30}$, kg N ha^{-1}) and the correlation coefficient ($R^2_{adjusted}$) in the 9 experiments where quadratic plus plateau (Q), exponential (EX) and quadratic (Q) regresssion models all yielded relationships with significant (P<0.10) coefficients

Experiment	$SUMN_{opt,30}$			$R^2_{adjusted}$		
	QP-model	EX-model	Q-model	QP-model	EX-model	Q-model
1	66	101	163	86	87	83
2	197	206	198	62	62	62
3	88	88	154	45	45	32
4	159	165	186	28	26	27
7	39	67	176	78	79	43
8	85	111	166	87	89	68
13	141	158	159	95	94	100
14	124	129	160	99	99	92
23	310	335	309	90	91	90
average	134	151	186	74	75	66

Table 8.3. Economically optimal N reserve (SUMN, kg N ha^{-1}, between parentheses s.e.) for silage maize at an early sampling stage, as related to the sampling depth and the price ratio of fertiliser N and silage maize DM, and the variance accounted for (averaged over 25 experiments)

Price ratio	Sampling depth (cm)	
	30	60
2.5	198 (20)	220 (20)
5	173 (15)	195 (15)
10	134 (13)	157 (13)
Variance accounted for (%)	72	74

reduce the economically optimal SUMN by circa 40 kg ha^{-1} and doubling the price of silage DM would increase the economically optimal SUMN by circa 25 kg ha^{-1}. Deeper sampling shifted the optimum to a higher value but did not result in larger VAF values.

The economically optimal SUMN varied considerably among experiments, as indicated by the standard error (s.e.) values. No significant (P<0.05) relationship was found between the attainable DM yield (range: 9600-18100 kg DM ha^{-1}) and the economically optimal SUMN.

8.4.3 Fixed N rate instead of early sampling

$SMN_{early,60}$ ranged from 8 kg N ha^{-1} up to as much as 324 kg N ha^{-1} because our data set included a few experiments where slurry had been applied in the six months before sampling. To date, the variation in $SMN_{early,60}$ will be much smaller, as present legislation prohibits manure application on sandy soils during winter in The Netherlands. The samples taken from treatments where no slurry had been applied in the preceding six months showed that in 63% of the cases less than 20 kg N ha^{-1} was found in the upper 30 cm and less than 40 kg N ha^{-1} was found in the upper 60 cm (Figure 8.1).

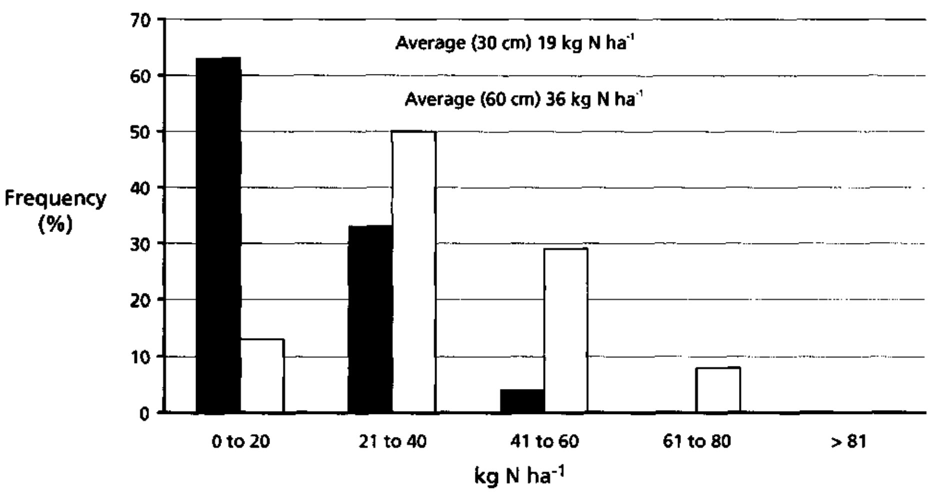

Figure 8.1. Frequency distribution (%) of the soil mineral N reserve in spring (SMN_{early}, kg N ha^{-1}) on sandy soils in treatments where no organic or mineral fertilizers had been applied in the preceding 6 months (■ = 0-30 cm depth, □ = 0-60 cm depth, n = 25 site years).

With such little variation, the usefulness of determining N requirements by assessing SMN_{early} may be questioned, as farmers can save the costs of sampling and analysis by simply applying a fixed N rate. We compared the financial margin of a fertiliser management strategy with variable rates (rate = 195 minus $SMN_{early,60}$; *cf.* Table 8.3) based on the yearly $SMN_{early,60}$ values observed in treatments where no slurry had been applied in the preceding six months, with the financial margin of a fertiliser strategy with a fixed rate of 160 kg N ha^{-1}. The financial loss associated with the use of a fixed rate was nil when averaged over the 25 site years. In only 8% of the cases, the loss exceeded NLG 25 ha^{-1} (representing a value of 25 kg N ha^{-1}) (Figure 8.2).

8.4.4 Optimal N reserve at late sampling date

The apparent daily increase of SMN between March-April and May-June was circa 0.20 kg N ha^{-1} d^{-1} for each 30 cm of soil depth in unfertilised treatments. However, there was substantial variation among experiments (Table 8.4). Delayed sampling may therefore reflect the amount of N ultimately available to a maize crop better than early sampling. As a result,

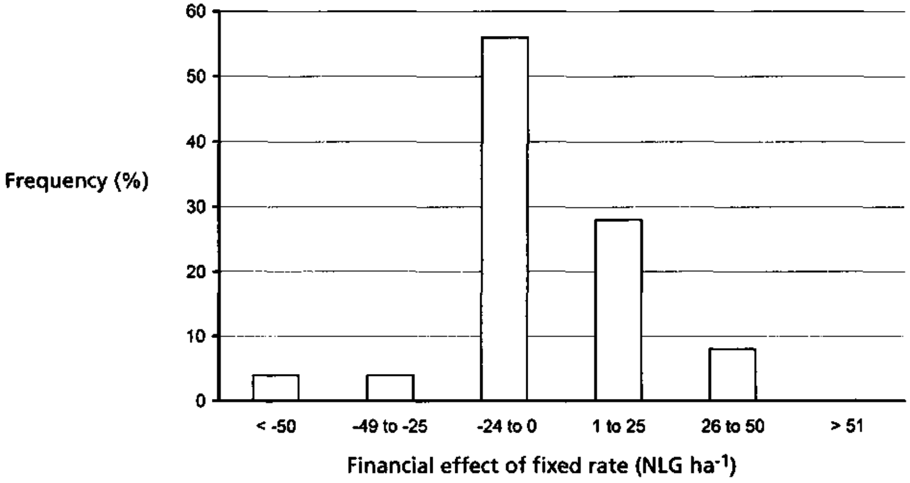

Figure 8.2. Frequency distribution (%) of the financial effect (NLG ha^{-1}) of using a fixed N rate of 160 kg ha^{-1} instead of variable N rate based on the presence of soil mineral N in spring (195 minus $SMN_{early,60}$; kg N ha^{-1}), as based on the N response functions in 25 experiments on sandy soils.

Table 8.4. Frequency distribution (%) of the average daily change in soil mineral N between the early (March-April) and late (May-June) sampling dates (kg N ha^{-1} d^{-1}) on sandy soils in treatments where no (organic) fertilisers had been applied in the 6 months prior to samplings (n = 20 site years)

Class (kg N ha^{-1} d^{-1})	Sampling depth (cm)	
	30	60
< -0.25	10	10
-0.24 - 0.00	15	0
0.01 - 0.25	30	15
0.26 - 0.50	30	25
0.51 - 0.75	10	30
> 0.75	5	20
average	0.21	0.39

Table 8.5. Economically optimal N reserve (s.e. in parentheses) for silage maize at an early sampling stage (SUMN, kg N ha^{-1}) and at a late sampling stage (SMN_{late}, kg N ha^{-1}), as related to the sampling depth, and the variance accounted for (averaged over 10 experiments)

Sampling stage	Early		Late	
Sampling depth (cm)	30	60	30	60
	175 (18)	203 (17)	147 (14)	229 (15)
Variance accounted for	63%	67%	70%	71%

yields may be related more to SMN_{late} than to SUMN. Variance accounted for by regression analysis, however, was only slightly larger when DM yields were fitted to SMNlate instead of SUMN, and the standard errors were not much smaller (Table 8.5). Again, deeper sampling did not result in larger VAF's. The economic optimum on the early (SUMN) and late (SMNlate) sampling dates did not differ significantly (P<0.10, pairwise t-test).

8.4.5 Effect of applied N on N uptake, silage yield, N surplus and residual soil N

Regression analysis showed a diminishing response of the N uptake to $SUMN_{60}$ in 18 of the 25 experiments (according to the Q or EX model) and a linear response (according to the L or LP model) in 7 experiments. This implies that in most cases, apparent N recoveries were larger at sub-optimal N reserves than at the economically optimal N reserve. Reduced N reserves had a smaller effect on DM yields than on N uptakes and, consequently, the N contents of the silage were positively related to the N reserve. Reducing the N reserve by 100 kg N ha^{-1} reduced the mineral N surplus ($NSURMIN_{ha}$)

Table 8.6. Average N uptake (kg ha^{-1}), apparent N recovery (ANR, %), N content (% in DM), DM yield (t ha^{-1}), relative DM yield (s.e. in parentheses), mineral N surplus per unit area ($NSURMIN_{ha}$, kg N ha^{-1}), N surplus per unit area including the organic N when manure is the source of N ($NSURTOT_{ha}$, kg N ha^{-1}), and the residual mineral N in the upper 60 cm after harvest ($RSMN_{60}$, kg N ha^{-1}), as affected by the mineral N reserve available to silage maize at an early sampling stage ($SUMN_{60}$, kg N ha^{-1})

	$SUMN_{60}$:					
	optimum[a]	optimum minus:				
		20 kg ha^{-1}	40 kg ha^{-1}	60 kg ha^{-1}	80 kg ha^{-1}	100 kg ha^{-1}
N uptake	186	180	172	163	153	140
ANR	53	57	61	65	69	73
N content	1.29	1.26	1.24	1.21	1.18	1.15
DM yield	14.49	14.32	14.01	13.56	12.96	12.21
relative DM yield	100 (0.0)	99 (0.1)	97 (0.4)	94 (0.9)	89 (1.6)	84 (2.5)
$NSURMIN_{ha}$ [b]	-26	-40	-53	-64	-74	-83
$NSURTOT_{ha}$ [b,c]	132	98	66	35	5	-22
$RSMN_{60}$	66	60	55	50	45	42

a when the price of 5 kg maize DM equals the price of 1 kg fertiliser, the optimal SUMN60 amounts to 195 kg N ha^{-1}(cf. Table 8.3).

b assuming an optimal SUMN60 of 195 kg N ha^{-1}, including 36 kg N ha^{-1} in early spring in the upper 60 cm (SMNearly,60).

c assuming that the mineral N : organic N ratio in manure = 1 (Beijer & Westhoek, 1996).

by 57 kg N ha^{-1}. The corresponding decrease of the total N surplus ($NSURTOT_{ha}$) was 154 kg N ha^{-1} if slurry had been the only N source. The calculated associated reduction of the DM yield averaged 16% (Table 8.6).
A positive relationship (P<0.01) was found between $SUMN_{60}$ and the residual SMN at harvest. Regression analysis indicated that the residue in the upper 60 cm would be 66 kg N ha^{-1} if maize were fertilised up to the economically optimal N reserve ($SUMN_{60}$) of 195 kg N ha^{-1} and 24 kg N ha^{-1} less when the N rate would have been 100 kg N ha^{-1} below that optimum (Table 8.6).

8.5 Discussion

8.5.1 The crop response to N

Analysis of 25 field experiments on the response of silage maize DM yields to N confirmed previous findings (Neeteson & Wadman, 1987; Sylvester-Bradley *et al.*, 1987; Cerrato & Blackmer, 1990) that the regression model chosen has a considerable effect on the calculated economically optimal N reserve. Quadratic models, which are inherently symmetrical, are especially likely to overestimate crop N demand when they are used to fit data showing no or just a gently negative response to N application rates exceeding the optimum (Neeteson & Wadman, 1987). Yet, many researchers including the corresponding author of this paper, have used these quadratic models uncritically (e.g. Russelle *et al.*, 1981; Onken *et al.*, 1985; Schröder *et al.*, 1993; Menelik *et al.*, 1994; Lory *et al.*, 1995; Schlegel *et al.*, 1996). Cerrato & Blackmer (1990) reported economically optimal N rates raising in the order QP<Q<EX, with the optima differing by as much as 68 kg N ha^{-1}. The optima in the experiments of our study that were equally well fitted by each of these three models, rose in the order QP<EX<Q, with the optima derived from the QP model being 52 kg N ha^{-1} lower than those from the Q model. Bullock & Bullock (1994) and Stecker *et al.* (1995) reported a similar shift of the economically optimal N rates due to the choice of either a Q or a QP model. This implies that a more critical choice of regression models may lead to lower N inputs. This could increase the recovery of N (Schröder *et al.*, 1993), lower the amount of residual soil mineral N (Schröder *et al.*, 1996b; Schröder, 1997) and would mitigate, if not resolve, the conflict between 'economics' and 'environment'.

8.5.2 Methodology to assess the optimal N reserve

N recommendations taking account of the soil mineral N present at the start of the growing season are usually derived from linear regression analysis of economically optimal rates against the soil mineral N reserves present in early spring (Neeteson, 1989b; Schmitt & Randall, 1994; Vanotti & Bundy, 1994b). The slope of the regression line indicates by how much the observed amount of soil mineral N in a specific soil depth should be multiplied before subtracting it from the base rate represented by the intercept. Such an approach requires data from experiments that differ in the amount of soil mineral N present at the start of the growing season. It was not possible to use this methodology in the analysis of the present data set, however, as in most cases the amount of soil mineral N was small and if it was not (as after application of slurry during winter in Experiments 1-8), too few fertiliser N treatments were superimposed to allow an accurate assessment of the optimum. Therefore, we considered SMN to be equivalent to the N in mineral fertiliser and the ammonium N in cattle slurry and plotted DM yields and N uptakes against the sum of all three sources of mineral N. It may be questioned whether ammonium N in slurry, mineral fertiliser N and SMN can be considered equally available to the plant. SMN is probably relatively evenly distributed over the profile, whereas mineral N from slurry or fertiliser will generally remain near the surface. Ammonium N from slurry and mineral fertiliser N may also differ in their availability to plants, as some ammonia will inevitably volatilise, even when the slurry is directly incorporated or injected, as in our experiments. On the other hand, gains resulting from mineralisation of the organic slurry fraction were also discounted and we assume that this compensated for the volatilisation. Experiments 3, 5, 6, 7 and 8 included sufficient treatments to enable us to calculate the economically optimal N reserve for treatments with mineral fertiliser only. The economic optimum was, on average, 13 kg N ha^{-1} lower, indicating that we may have slightly overestimated the mineral N contributed by spring-applied slurry.

8.5.3 Calculated optimal N reserve for early and late sampling

We calculated an economically optimal reserve 0-3 weeks before planting (SUMN) of 173 and 195 kg N ha^{-1} for sampling depths of 30 cm and 60 cm, respectively. Variation in SMN_{early} on soils that had not been manured in the preceding six months, appeared to be too small to compensate for the costs of soil sampling and analysis. Under those circumstances a fixed rate of circa 160 kg mineral N ha^{-1} is appropriate to attain the N reserve required for the highest economic return. However, on heavier soil types SMN_{early} can be much higher after e.g. a dry winter; soil sampling and analysis may then pay off.

Sampling 3-4 weeks after emergence indicates to what extent inputs have been lost, have become temporarily immobilised, or have been augmented with N released from mineralisation (Magdoff, 1991). Late sampling should not, however, be considered a component of a deliberate split application strategy in which N rates are tuned to the amount assessed in the late sample. Contrary to the findings of Magdoff (1991) and Blackmer *et al.* (1989), research in The Netherlands has shown no clear positive effects of delayed N applications on N use efficiency (Schröder, 1997). Hence, late sampling should at best be considered a check on the fate of earlier applied N in an exceptionally cool and wet spring. We calculated a late economically optimal reserve of 147 N ha^{-1} for a sampling depth of 30 cm and 229 kg N ha^{-1} for a depth of 60 cm. Similarly to what Binford *et al.* (1992a) concluded, the variance accounted for did not increase by inclusion of the 30-60 cm of soil in the sample. It nevertheless appears worthwhile to sample the whole 0-60 cm, as otherwise N that has moved to the 30-60 cm depth in a wet spring may be overlooked (Blackmer *et al.*, 1989; Schmitt & Randall, 1994). Schröder (1997) concluded that to make a post-emergence mineral fertiliser supplementation profitable, the soil mineral N reserve 4 weeks after emergence must be as low as 175 kg N ha^{-1} (0-60 cm of soil). This is in reasonable agreement with the critical values of 20-25 mg nitrate N per kg soil found by Fox *et al.* (1989), Klausner *et al.* (1993) and Schmitt & Randall (1994).

8.5.4 Comparison with recommendations elsewhere

Our findings concerning the economically optimal reserve cannot be compared directly with the results from others, due to the differences in sampling time, manuring history, price ratios of the product and fertiliser N, emphasis on grain instead of silage yields or an arbitrary choice of regression models. Moreover, some studies are confined to soil nitrate instead of nitrate and ammonium together. Nevertheless, if we assume that 20, 15 and 10 kg mineral N ha^{-1} can be found in early spring in the 0-30, 30-60 and 60-90 cm layers, respectively, our recommendation to apply 153-160 kg mineral N ha^{-1} (i.e. 173 minus 20 $SMN_{early,30}$ or 195 minus 35 $SMN_{early,60}$) agrees well with the results from Bassel *et al.* (1987), Beauchamp & Kachanoski (1989) and Vanotti & Bundy (1994a, b). Using their formulas yielded recommended N rates of 152-188 kg ha^{-1}.

Our economically optimal late N reserve of 147 kg N ha^{-1} in the upper 30 cm is equivalent to circa 35 mg soil mineral N per kg soil. This is considerably more than 20-30 mg kg^{-1} N (nitrate only) recommended by Magdoff (1991) and Binford *et al.* (1992a). Our economically optimal late N reserve of 229 kg N ha^{-1} in the upper 60 cm is equivalent to circa 28 mg soil mineral N per kg soil. This is only slightly more than the 25 mg kg^{-1} recommended for this depth by Blackmer *et al.* (1989).

8.5.5 Target yield level and the optimal N reserve

The economically optimal reserve varied greatly but higher yields did not generally justify higher N rates. A similar conclusion was drawn by Vanotti & Bundy (1994a, b) and Schlegel *et al.* (1996). It seems that economically optimal reserves are mainly determined by factors such as the N supplying capacity of a soil and the ability of a maize crop to recover mineralised and applied N. A high N supplying capacity and pedo-climatic conditions favouring the recovery of fertiliser N, will thus decrease the economically optimal N reserve.

8.5.6 Agronomic and environmental effect of a sub-optimal N reserve

The apparent N recoveries of maize were lower when N was applied at the economically optimal reserve than when N was applied at rates below this, as reported earlier for potatoes (Neeteson *et al.*, 1987) and some vegetable crops (Greenwood *et al.*, 1989). Hence, maximizing the economic returns of maize production (i.e. by applying the economically optimal N rate) is associated with much higher risks of N losses. Reduction of the N rate by 100 kg N ha^{-1} below the economically optimal reserve reduced DM yields by 16% on average, while the mineral N surplus dropped by 57 kg N ha^{-1}. This was only partly reflected in the amount of residual soil mineral N in the upper 60 cm, which was 24 kg N ha^{-1} lower than when optimally fertilised. This relatively small effect on mineral N residues is due to the fact that some of the surplus is lost during the growing season, possibly through leaching in early spring and late summer (Wantulla *et al.*, 1988; Schröder *et al.*, 1993; Schröder *et al.*, 1996b; Schröder, 1997). The observed residues justify reducing N inputs in conventional maize production systems in The Netherlands because, assuming a realistic precipitation surplus of circa 300 mm, not more than 34 kg N ha^{-1} should leach into groundwater to keep its nitrate content below the threshold value of 11.3 mg nitrate N l^{-1} (Anonymous, 1980). Soil mineral N residues of the observed magnitude are only acceptable when nitrate is denitrified at greater depths or when the nitrate emission from maize land is compensated for by nearby land use with a much lower emission.

The mineral N surpluses ($NSURMIN_{ha}$) that we calculated are strongly negative at sub-optimal N reserves, indicating that the N supplying capacity of the soils under study was large. This is not unlikely, because the manuring practice on maize land in The Netherlands has a notable residual effect (Whitmore & Schröder, 1996). A negative N surplus implies that the soil fertility is gradually depleted if no other N is input except for the mineral N input terms of our calculation. Consequently, the associated yield penalty could well become larger in the long run (Whitmore & Schröder, 1996; Schröder & Van Keulen, 1997). However, the depletion is compensated for by the common input of N through organic N in manure, as indicated by the calculated total N surplus ($NSURTOT_{ha}$; Table 8.6). Atmospheric deposition in

The Netherlands (circa 40 kg N ha^{-1} yr^{-1}) also contributes to a positive balance of N inputs and outputs.

If atmospheric deposition and organic N inputs were smaller than to date in The Netherlands, the soil organic N pool would much more likely become depleted. The only way to avoid such a gradual increase of the yield depression due to depletion, would be to rotate silage maize with crops that are associated with a positive effect on the soil organic N pool (grass leys, lucerne).

One possible way to mitigate the negative effect of a sub-optimal fertiliser N application on yields might be to use alternative cropping techniques. Accurate placing of fertiliser and manure, for instance, may boost the N recovery and reduce N emission whilst maintaining yield levels (Schröder *et al.*, 1996a; Schröder *et al.*, 1997b; Van Dijk, 1996). Cover cropping could be another component of such alternative cropping techniques, because cover crops can prevent soil mineral N residues from leaching and can contribute to the N requirement of a next maize crop (Schröder *et al.*, 1996b).

To sum up, adjusting the N input to a level below the economically optimal reserve can reduce the risks for N losses to the environment associated with conventional maize production, with a limited effect on silage yields.

CHAPTER 9

GENERAL DISCUSSION

9.1 Evaluation and conclusions

9.1.1 Objectives

The ability of a forage crop to convert soil nitrogen into a useful feedstuff depends on various underlying processes that include *1)* the crop's uptake of soil nitrogen (N), *2)* the utilisation of crop N for the production of harvestable dry matter and *3)* the nutritional value of the material harvested. As far as the last two processes are concerned, maize is an extremely efficient forage crop. Seventy to hundred kg harvestable dry matter (DM) can be produced per kg nitrogen (N) taken up (Figure 9.1). Moreover, maize produces highly digestible DM over a broad range of growing conditions (Struik, 1983).

In this thesis only the first process is considered. It was the inefficiency of maize in taking up soil N that led to the research described in this thesis. As pointed out in the Introduction (Chapter 1) the research had the following objectives:

- to identify and to increase our understanding of *factors* that determine the partitioning of N inputs over crop and losses, with emphasis on maize grown on sandy soils in The Netherlands,
- to provide *techniques* to improve the N efficiency of maize crops,
- to integrate these techniques into a consistent, comprehensive and environmentally sound N management *system*.

The following three sections discuss the effects of the rates (9.1.2), placement (9.1.3) and timing (9.1.4) of N application on N recovery. These sections are followed by a discussion of the amounts of residual soil mineral N left by maize crops and of their implications for nitrate leaching (9.1.5 and 9.1.6). Subsequently, the potential for growing cover crops is discussed (9.1.7). Finally, recommendations for an environmentally sound cropping system are given (9.1.8).

The feasibility of the recommendations is addressed in section 9.2. In the following section (9.3) the findings presented in this thesis are matched against the anticipated Dutch legislation on the use of manure and fertiliser.

Recommendations for future research are given in section 9.4. and the findings are summed up in section 9.5.

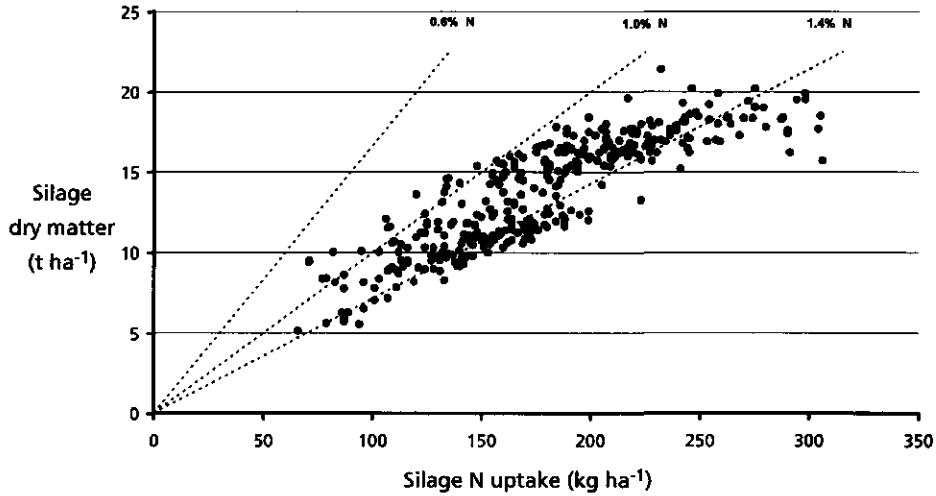

Figure 9.1. Relationship between the N uptake and DM yield of silage maize at maturity (combined data of the experiments reported in Chapter 8).

9.1.2 Effect of application rates on N recovery

The analysis of 25 field trials presented in Chapter 8 revealed that the apparent N recovery (ANR) of the soil mineral N present in spring averages 53% when maize is fertilised at the economically optimal N rate. This is in agreement with typical values obtained from the literature reviewed in Chapter 1. The ANR value of maize is lower than the ANR values reported for cut grassland, sugar beet and wheat (Prins *et al.*, 1988).
Nitrogen recovery values for maize decrease even further when N inputs exceed crop N requirements. Excessive application of N has been and still is a common phenomenon in The Netherlands, as maize growers tend to apply large amounts of N to dispose of the slurry produced on their livestock farms. Moreover, considerable amounts of mineral fertilisers are applied in addition to slurry, to compensate *a priori* for possible N losses.
The N recovery can increase considerably at low application rates of N. According to an analysis described in Chapter 8, ANR values for mineral N rise from 53% for optimally fertilised maize to 73% at an application rate of 100 kg N ha^{-1} below the optimum, though this is achieved at the expense of depressing yield by 16%. Such a negative relationship between the input

rate and the ANR can also be derived from the data on spring-applied slurry presented in various chapters of this thesis. The ANR for slurry applied at rates of 121 (Chapter 3), 164 (Chapter 6), 249 (Chapter 4) and 343 kg total N ha^{-1} (Chapter 5), are 36%, 48%, 29% and 15%, respectively. The recovery of slurry N and mineral fertiliser N is determined not only by the amount applied but also by the placement and the timing of the application.

9.1.3 Effect of placement on N recovery

As for the placement, this thesis confirmed that nutrients should preferably be applied in those parts of the soil profile where they can be easily intercepted by the root system. Initially, the root length is limited and relatively high N uptake rates per unit root length are required. Figure 9.2, based on the N uptake rates derived from Figure 1.5 (Chapter 1) and the root lengths derived from Chapter 2, illustrate this shift in N uptake per unit root length.

The experiments in the Wageningen Rhizolab reported on in Chapter 2, indicated that it takes a long time for roots to penetrate greater depths and to extend laterally into the soil in between the maize rows. It was shown that root length densities in the various soil compartments appear to be

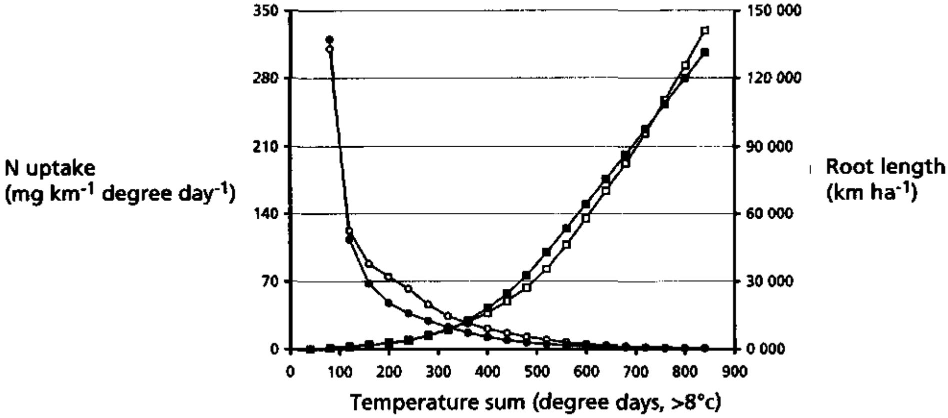

Figure 9.2. Root length (km ha^{-1}; □ = non-deficient and ■ = N deficient silage maize) and N uptake per unit root length (mg km^{-1} day $degree^{-1}$; O = non-deficient and ● = N deficient silage maize) as related to thermal time after planting (threshold >8 °C); based on data from Chapters 1 and 2.

more strongly related to thermal time than to calendar time. The data from the Rhizolab experiments agreed reasonably well with root length densities observed in the field experiments described in Chapter 3 (Figure 9.3). The vertical and horizontal gradients found in these experiments were similar to those found in the Rhizolab. From this, it can be concluded that positioning slurry or mineral fertiliser too deeply should be avoided, because initially many roots have not yet reached these depths. Therefore, tillage operations need to be tailored to the methods of slurry and fertiliser application and *vice versa*. The root length density gradients in the horizontal plane make it a more attractive option to plant maize close to the slurry or fertiliser application slots than to plant in between the slots. This is evidenced by the positive response of the ANR value to row application of slurry and mineral fertiliser (Chapters 2 and 3). Similar conclusions were recently drawn by Van Dijk (1996). Changing the sequence of operations i.e. by planting first and then applying slurry or fertiliser instead of the other way around, appears to be a less effective option (Chapter 5).

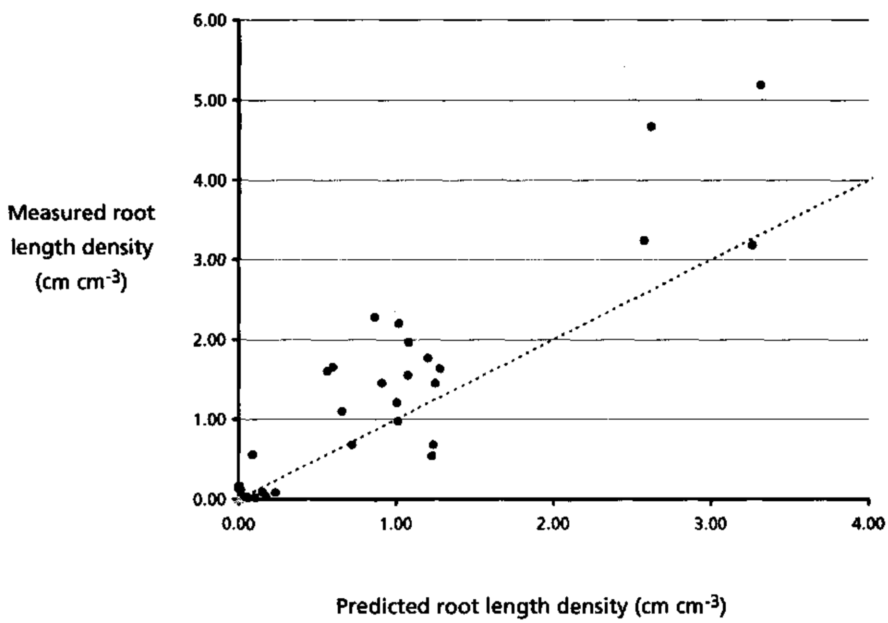

Figure 9.3. Relationship between predicted root length densities (Chapter 2) and observed root length densities of maize (Chapter 3); ----'y = x'.

9.1.4 Effect of timing on N recovery

As for the timing, in The Netherlands it is illegal to apply slurry on sandy soils from September 1 to February 1. The experiments presented in Chapter 4 endorse the imposition of this ban. Spring-applied slurry contributes more to the availability of N to the crop than autumn-applied slurry, even when autumn-applied slurry is amended with a nitrification inhibitor. The results also indicate that postponing the slurry application until February 1, does not guarantee a high recovery of slurry N. Better chances for a high recovery are undoubtedly provided by setting the the time of application closer to the date of maize planting (i.e. the end of April). A further postponement until after crop emergence, however, does not seem to increase the recovery. In Chapter 5 it was concluded that this is due to crop damage, to volatilisation losses when slurry is the source of N and to an inappropriate timing and placement of N.

9.1.5 Residual soil mineral N

In all field trials discussed in Chapters 4, 5, 6 and 7, positive relationships were found between the amount of N input and the amount of residual soil mineral N (RSMN) left at the time of harvest. In Chapter 8 it was calculated that, on average, 66 kg N ha^{-1} remains in the upper 60 cm of soil when the economically optimal N supply is applied to maize. However, the observed increase of RSMN resulting from the use of mineral N from either slurry or fertiliser is usually less than the difference between the amount applied and the amount taken up by the crop. Twenty to thirty percent of the mineral N input is generally not accounted for in either crop or soil at harvest. Some of this N may have been lost through volatilisation if manure was the source of N. Another part may have become immobilised by microbes foraging on decaying maize roots. Root decay sets in at the end of July, after flowering (Mengel & Barber, 1974; Chakravarty & Karmakar, 1980). At that moment maize roots represent circa 1000 kg carbon (C) ha^{-1} with a C to N ratio of about 40 (Thom & Watkin, 1978; Anderson, 1988). Decomposition of such material is often associated with microbial immobilisation of soil mineral N (Whitmore, 1996).

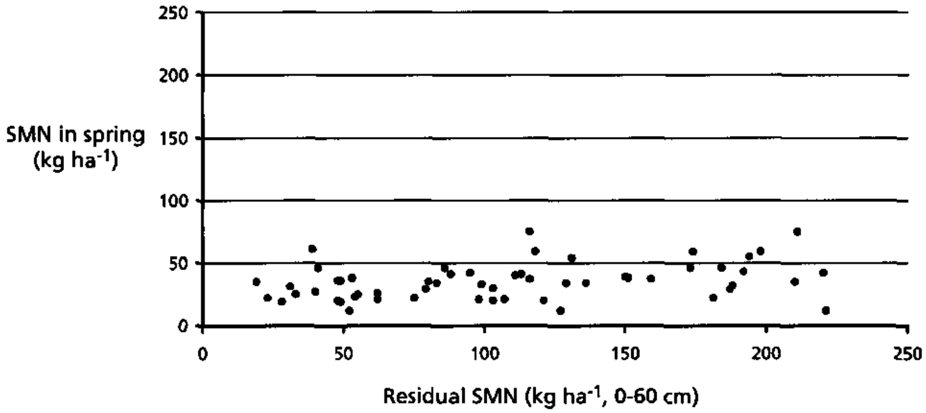

Figure 9.4. Soil mineral N supply (SMN, 0-60 cm) in spring, as related to the residual soil mineral N supply (RSMN, 0-60 cm) in the preceding autumn (combined data of the long-term trials on sandy soils with precipitation surpluses ranging from 207 to 629 mm, reported in Chapters 4, 5 and 6).

The results presented in Chapters 4, 5 and 6 indicate that RSMN is inversely related to summer rainfall. This observation cannot always be explained by the positive effect of summer rainfall on crop yields and crop N uptake and therefore leaching and denitrification are also probably responsible for the loss of N. The results from the experiments described in Chapters 4, 5 and 6 indicate that leaching losses may indeed occur during the growing season, confirming the findings of Wantulla *et al.* (1988) and Torbert *et al.* (1992; 1993).

The amount of RSMN is indicative of the losses from maize land during winter as most of this land is left fallow during this season and the soil's capacity to retain N is limited, especially if the soil is sandy. Pooled data from the long-term trials described in Chapters 4, 5 and 6 illustrate this limited retention of N. During winter, SMN reserves converge to a constant value in spring, irrespective of the reserves present in the preceding autumn (Figure 9.4).

9.1.6 Nitrate losses

The pooled data from the experiments described in Chapters 4, 6 and 7 suggest that the amount of RSMN correlates with the amount of nitrate lost by leaching (Figure 9.5). The risk of leaching is not merely the result of the presence of RSMN, however. Balance sheet calculations made for the experiments described in Chapters 4 and 6 indicate that the amount of SMN in spring is generally larger than the difference between the amount of RSMN in the preceding autumn and the amount of N lost by leaching. This implies that the balance of mineralisation, immobilisation and denitrification is positive not only during summer but also during winter. A positive relationship (P<0.05) can be observed between the outcome of this balance and the cumulative day degrees between the times of soil sampling in autumn and in spring. In an average winter (1 October - 1 April) with a typical heat sum of circa 1000 degree days, mineralisation exceeds the sum of immobilisation and denitrification by circa 20 kg N ha^{-1}, on average (Figure 9.6). It is possible that this mineralisation arises from the organic N pool developed by the surmised microbial immobilisation associated with root decay. Obviously, nitrate leaching would increase even more if slurry applications in autumn and winter were still permitted on sandy soils in The Netherlands; this is demonstrated by the experiments presented in

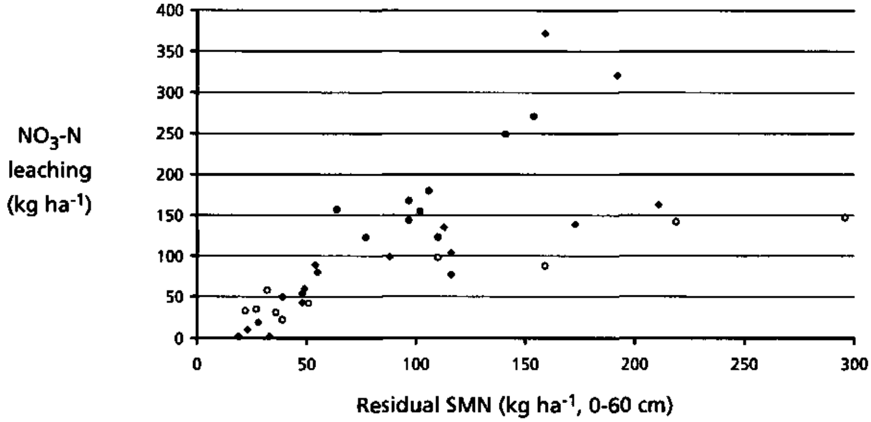

Figure 9.5. Nitrate-N leaching (kg N ha^{-1}) during winter from a soil depth of 100 cm, as related to the residual soil mineral N supply (0-60 cm) in the preceding autumn (combined data of the experiments reported in Chapters 4 (O), 6 (◆) and 7 (●)).

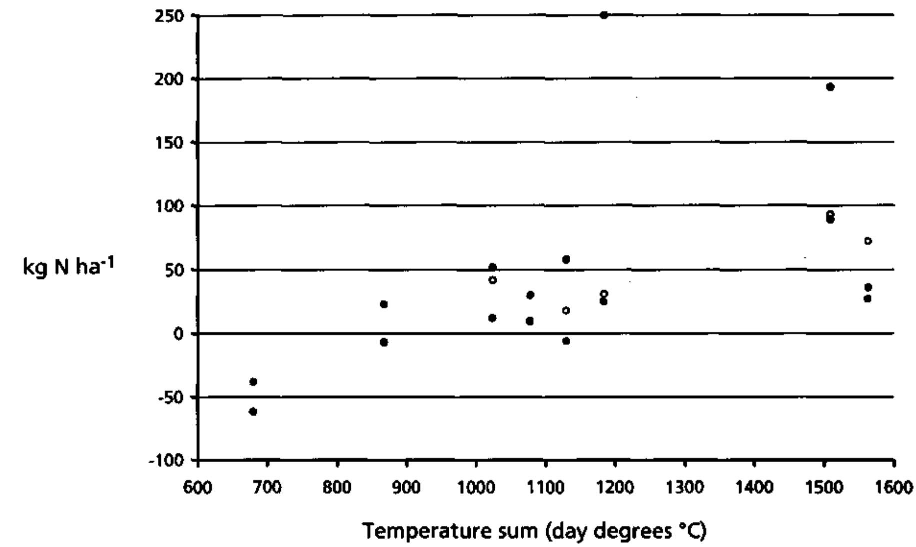

Figure 9.6. Balance of mineralisation, immobilisation and denitrification (accounting for the amount of N leached and the change of soil mineral N between autumn and spring), as related to the cumulative day degrees (threshold > 0 °C) between the times of autumn and spring soil sampling (O = without N inputs in preceding growing season, ● = with N inputs in preceding growing season).

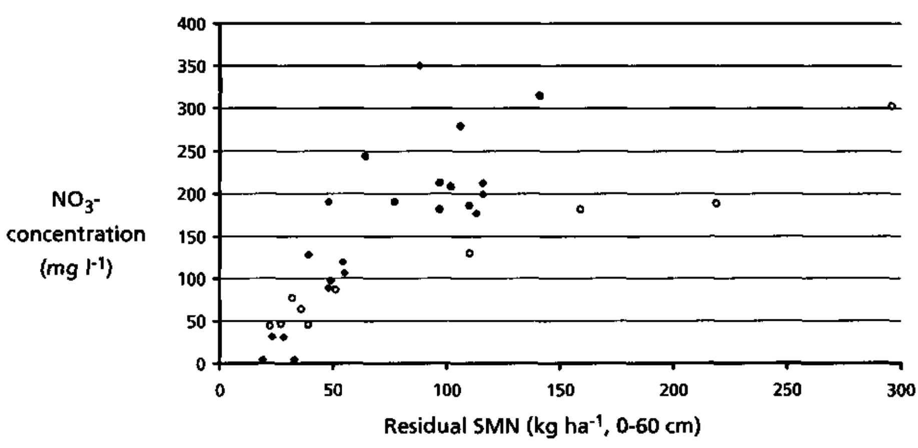

Figure 9.7. Average nitrate concentration (mg NO_3 l^{-1}) in groundwater during winter at a depth of 100 cm, as related to the residual soil mineral N supply (0-60 cm) in the preceding autumn (combined data of the experiments reported in Chapters 2(O), 6(◆) and 7(●)).

Chapter 4. As this thesis has demonstrated, the nitrate concentrations in the shallow groundwater exceed a value of 50 mg l^{-1} when more than circa 30 kg RSMN ha^{-1} are left by the maize crop in the upper 60 cm of the soil (Figure 9.7). Such amounts of RSMN seem inevitable when maize is grown in a conventional way and when the crop is fertilised at the economically optimal N rate, as indicated in Chapter 8.

9.1.7 Cover crops

Cover crops appear to be a simple and appealing measure for sequestering RSMN and preventing nitrate leaching. The experimental results presented in Chapter 6 make clear that the N uptake potential of cover crops grown after maize is limited by the weather. These experiments, and those conducted on De Marke experimental farm (Schröder & Ten Holte, 1996), indicate that the uptake capacity of a cover crop after maize averages 30-40 kg N ha^{-1}. This implies that maize growers cannot expect cover crops to fully avoid the leaching problem resulting from RSMN and mineralisation during winter. It appears that additional measures are needed to prevent the accumulation of RSMN. Moreover, growers should make every effort to create conditions that encourage the cover crop to establish early and that enhance N uptake. They can do so by using early maturing maize varieties and by avoiding too dense plant populations in their maize crops. Both these measures facilitate an early harvest of the maize. When the amount of RSMN matches the uptake capacity of the cover crop, cover crops can indeed be an effective way of reducing nitrate leaching considerably. The results presented in Chapter 6, imply that leaching losses can be reduced by circa 40 kg N ha^{-1} by growing cover crops.

9.1.8 Recommendations

Returning to the initial objectives of the thesis, it can be concluded that N losses resulting from the current technique for cropping maize on Dutch sandy soils, can be attributed to a combination of factors:

- too high application rates of N due to regional slurry surpluses and a tendency for maize growers to compensate *a priori* for unforeseen N losses,

- inaccessibility of the soil N for roots in a cold and wet spring,
- too early or too late applications of N,
- application of N in non-rooted or poorly rooted soil compartments,
- N mineralisation outside the period that maize takes up N.

From the research described in this thesis it is concluded that maize growers can reduce N losses by using the following cropping *techniques*. These techniques will only become effective, however, if they are used concomitantly in a consistent and comprehensive *system*:
- drastically reducing the N application rate (including manure N),
- fine-tuning the application rate of N by taking account of site characteristics such as the intrinsic soil mineral N reserves, the manuring history and the N contribution from previous crops including cover crops,
- confining the application of N to those parts of the soil profile where a high root length density is anticipated,
- postponing the application of N until shortly before sowing,
- restricting post-emergence applications of N to situations where N deficiency is indicated by the soil mineral N reserves,
- growing cover crops after maize.

9.2 Feasibility and practical implications of the recommendations

It is useful to relate the findings of this thesis to the current practice of maize cropping. It is only fair to say that many of the previous recommendations inevitably cost money: more soil sampling costs, investments in alternative techniques for applying slurry and mineral fertilisers and expenses incurred by cover cropping. Cover crops may also require concessions to the length of the maize growing season and, hence, the productivity of the crop, to ensure a timely establishment of the cover. Last but not least, it must be noted that reduced application rates of slurry will force some maize growers to spend extra on removing excess slurry from their farms.

Various other factors besides costs may hamper the introduction of an environmentally sound cropping system for maize. One is the practice of continuous cropping of maize, which is the rule rather than the exception today. Root rot incidence increases at high cropping frequencies (Scholte,

1987) and this may reduce the ability of a maize crop to take up nutrients (Scholte & s' Jacob, 1983). Continuous cropping also reduces the possibility to insert vigorous cover crops in the rotation. Moreover, continuous cropping of silage maize can result in an imbalanced availability of plant nutrients. Since it is extremely difficult to manure so that one element is applied at the desired level without depletion or accumulation of the other elements (Schröder, 1990c; Schröder & Van Dijk, 1995), reduced manure inputs directed at improving N recovery may in the long run be counteracted by phosphorus (P) deficiency (Schlegel & Havlin, 1995), potash (K) deficiency (Schröder & Dilz, 1987; MacKenzie *et al.*, 1988) or by a too low pH (Goodroad & Jellum, 1988). As a result, the practice of continuous cropping may need to be reconsidered. In a crop rotation with grass leys, for instance, slurry application can replenish the P and K reserves of the soil with only limited risks of N leaching if the application takes place in the grassland phase of the rotation.

Another handicap for an environmentally sound cropping system is that most field operations are done by contractors. The recommendation to postpone the application of slurry to the end of April and to have the application preferably integrated with tillage and planting operations, may conflict with the desire of contractors to spread the work over as long a period as possible. Moreover, the recommendation to establish cover crops early may not yet be feasible in view of the limited capacity of maize harvesters.

9.3 Anticipated legislation and nitrate-safe scenarios

9.3.1 Outlines of MINAS legislation

It is also relevant to evaluate how the results of this thesis relate to the anticipated Dutch legislation on the use of manure and fertilisers. Legislation will change within a few years from an input-oriented approach to a surplus-oriented approach. The legislation aims at a drastic reduction of the risks of nitrate leaching (Oenema *et al.*, 1997). Dutch farmers will be forced to keep records of all the N and phosphate (P_2O_5) entering or leaving the farm. This mineral accounting system, called MINAS, is directed at the whole-farm level. When inputs exceed the outputs, a levy will be charged on the surplus.

Surpluses are levy-free up to a certain level which declines from a surplus of 40 kg P_2O_5 ha^{-1} in 1998 to a surplus of 20 kg P_2O_5 ha^{-1} in 2008. Above this level, the levy will be NLG 5 per kg P_2O_5 for the first 5 kg surplus and NLG 20 per kg P_2O_5 for every subsequent kg. The levy-free surplus of N depends on the crop types present on the farm. It will decline from 175 kg N ha^{-1} in 1998 to 100 kg N ha^{-1} in 2008 for arable crops and from 300 kg N per ha in 1998 to 180 kg N ha^{-1} in 2008 for grassland. Surpluses above these levels will be charged NLG 1.50 per kg N (Anonymous, 1995, 1996b; Oenema *et al.*, 1997). It is left to the farmer to decide how to stay below the levy-free surplus. Therefore, from 2008 a surplus larger than 100 kg N ha^{-1} will be theoretically permissible on maize land, as long as the whole-farm surplus does not exceed the weighted average of levy-free surpluses for arable crops and grassland. Strictly speaking, MINAS can therefore not be evaluated for an individual crop unless maize is the only crop grown on the farm. Nevertheless, the agronomic and environmental consequences of MINAS will be explored below, using the relationships between the mineral N input, the N uptake, the silage DM yield, the soil mineral N residue and the nitrate concentration in the upper groundwater, established in this thesis.

9.3.2 Nitrate-safe maize cropping scenarios

Generally, MINAS constrains the manure inputs via the permitted P surplus and not via the permitted N surplus. Hence, MINAS leaves maize growers the opportunity to supplement with mineral fertiliser N. Most maize growers will probably extend the use of slurry on maize land to such an extent that the P surplus raises from 20 to 25 kg P_2O_5 ha^{-1}. Consequently, they will be charged for exceeding the levy-free level of 20 kg P_2O_5 ha^{-1} by 5 kg ha^{-1}. Based on current P contents in slurry (Beijer & Westhoek, 1996), this will cost them NLG 10 to NLG 20 per m^3 slurry, but this is less than the costs of alternative means of disposing the slurry. Moreover, it will save maize growers some mineral fertiliser N.

First, the implications of MINAS can be ascertained by considering a cropping system directed at optimizing the N supply for the production of silage. The definition of such a cropping system is derived from Chapter 8. In that chapter it was concluded that the sum of available soil mineral N (0-60 cm depth), ammonia N from slurry and N from mineral fertiliser, must be 195 kg N ha^{-1}. It is useful to take account of a future decrease of the N supply due to a gradual reduction of the atmospheric N deposition and decreasing residual effects from former manure applications. To do so, two types of environment were distinguished: present environments with a high N supplying capacity and future environments with a low N supplying capacity. The difference between these two is set at 30 kg N ha^{-1} yr^{-1} for the summer and 10 N ha^{-1} yr^{-1} for the winter period. These estimates are based on Chapter 7. Further definitions, assumptions and calculations are given in Appendix 1.

According to the calculations (following Appendix 1), MINAS allows farmers to apply as much N to maize as needed for an optimal N supply in an environment with a high N supplying capacity, and almost sufficient N in an environment with a low N supplying capacity (Table 9.1). However, both cropping systems result in nitrate concentrations in the shallow groundwater exceeding the EC Nitrate Directive for drinking water (Anonymous, 1980) by a factor 2 to 3.

Having established that MINAS alone will generally not yield nitrate concentrations lower than 50 mg l^{-1} under maize land, I explored what kind of additional cropping techniques are required for acceptable nitrate concentrations. I confined myself to the techniques examined in this thesis, i.e. fallowing versus cover cropping during winter and broadcasting versus placement of slurry and fertilisers. The estimated effects of cover cropping are derived from Chapter 6, the estimated effects of N placement from Chapters 2 and 3. The results presented in the latter two chapters indicate that placement may increase the recovery of N 1.2 - 1.4 times. Van Dijk (1996) reported that placement of mineral fertiliser N improved recovery by a factor of 1.4. In my calculations I adopted a value of 1.25, as it may be prudent and practical not to apply all N close to the plant.

I calculated that when the N supplying capacity of the environment is high, it is simply impossible to make the conventional cropping system yield a nitrate concentration of 50 mg l^{-1} or less. Even without N inputs from fertiliser or slurry, I estimated that the nitrate concentration would be 64 mg l^{-1} (Table 9.2). In environments with a high N supplying capacity, cover crops appear indispensable to achieve nitrate concentrations of less than 50 mg l^{-1}, whilst using slurry. Consequently, the financial margins can be improved considerably by using cover crops under these circumstances. The N supply for maize can still be optimal, especially if cover crops are combined with N placement. Under the present circumstances cover cropping pays off, as its costs are estimated to range from NLG 70 - NLG 150 per ha. N placement adds little more to the financial margin, indicating that the costs of this technique must be small to make it profitable.

When the N supplying capacity is low, the nitrate concentration in groundwater may fall to 50 mg l^{-1} or less when the N input is drastically reduced. This will cost the maize grower almost 2 t silage DM ha^{-1}. However, N placement can limit the yield penalty considerably. The yield depression is even less when a cover crop is grown. The financial margins of cropping systems with N placement or cover cropping are similar and seem sufficiently high (compared to the alternative without N placement and cover cropping) to compensate for the expenses.

In these calculations I have not taken account of the high costs of removing slurry from the farm or of buying in forage. Cover cropping allows a grower to recycle more slurry within the farm to increase his forage production and, hence, to make it less necessary to export slurry and to import forage. Consequently, I may have underestimated the positive effect of a cover crop on the farmers income when he is confronted with a policy which directly relates his farming practice to the nitrate concentration in groundwater.

Table 9.1. N inputs, N surplus, DM silage yields, nitrate concentrations in groundwater and the financial margin of a cropping system directed at applying as much N as needed to yield at least 5 kg silage DM per kg N input (constraints: P surplus less than 25 kg P_2O_5 ha^{-1} yr^{-1}, N surplus (without deposition) less than 100 kg N ha^{-1} yr^{-1}, cattle slurry is preferred to mineral fertiliser N, no denitrification at greater depths). *Definitions, assumptions and calculations are given in Appendix 1.*

N supplying capacity of the soil		high	low
Mineral fertiliser N (kg ha^{-1})	NFER*	19	28
Ammoniacal N from slurry (kg ha^{-1})	NH4N*	136	136
N available to maize (kg ha^{-1})	SUMNP*	195	186
N surplus (kg ha^{-1})	NSMINAS*	88	100
Nitrate concentration (mg l^{-1})	NO3C*	162	111
DM yield (t ha^{-1})	DMYMA*	15.0	14.9
Financial margin (NLG ha^{-1})	FRET*	3530	3490

* Acronyms used in Appendix 1.

Table 9.2. N inputs, N surplus, DM silage yields, nitrate concentrations in groundwater and the financial margin of a cropping system directed at applying as much N as needed to yield at least 5 kg silage DM per kg N input whilst attempting to bring down the nitrate concentration in the groundwater to 50 mg l^{-1} or less, as related to the use of cover crops and N placement (constraints: P surplus less than 25 kg P_2O_5 ha^{-1} yr^{-1}, N surplus (without deposition) less than 100 kg N ha^{-1} yr^{-1}, cattle slurry is preferred to mineral fertiliser N, no denitrification at greater depths). *Definitions, assumptions and calculations are given in Appendix 1.*

N supplying capacity of the soil	high			low			
Cover crop (y=yes, n=no)	n	y	y	n	n	y	y
N placement (y=yes, n=no)	-	n	y	n	y	n	y
Mineral fertiliser N (kg ha^{-1})	0	0	0	0	0	24	0
Ammonia N from slurry (kg ha^{-1})	0	117	114	85	113	136	128
N available to maize (kg ha^{-1})	40	170	195	107	163	195	195
N surplus (kg ha^{-1})	-102	41	25	13	36	93	53
Nitrate concentration (mg l^{-1})	64	50	19	50	50	28	0
DM yield (t ha^{-1})	9.1	14.7	15.0	13.3	14.7	15.0	15.0
Financial margin (NLG ha^{-1})*	2270	3540	3600	3210	3520	3520	3590

* exclusive costs of N placement and cover cropping

The N surpluses associated with my 'nitrate-safe' scenarios are considerably less than the levy-free surplus of 100 kg N ha^{-1} set by MINAS for 2008 and much lower than the even higher surpluses still permitted until that year. Hence, without additional measures, MINAS will probably not yield an acceptable nitrate concentration in the shallow groundwater under maize land. The need for additional measures such as suboptimal N inputs, cover cropping and N placement could be considerably less on soil types where the contamination of deeper groundwater with nitrate is limited due to denitrification (Oenema *et al.*, 1997). However, most maize is grown on freely draining sandy soils with a deep water table and under such conditions losses due to denitrification are of limited significance.

9.4 Recommendations for future research

Not unexpectedly, this thesis leaves several questions unanswered and poses new ones. The findings described in this thesis may serve as input data in models in three ways, in order to further evaluate the results and to extrapolate them to various levels of integration.
Firstly, in case of a row crop such as maize, two-dimensional models, accounting for both the vertical and lateral components of soil water, nutrients and rooting dynamics (De Willigen & Van Noordwijk, 1987; Heinen, 1997; De Vos, 1997), may help to better define the pedoclimatic regions in which N placement and N splitting are profitable. In addition to the usual attention given to the impact of excess water on the availability of N, the effects of drought on the availability of N deserve also attention (De Willigen & Van Noordwijk, 1995). Moreover, two-dimensional models may help us to design efficient experiments and to identify efficient rooting strategies which contribute to the definition of ideotypic genotypes. Maize genotypes may show a substantial variation in shoot and root traits which may affect the N use efficiency (Clark, 1983; O'Toole & Bland, 1987). These aspects need to be addressed in future experimental work as well, as we do not fully understand the existing genotypic variation and the practical significance of these traits on a whole crop level.
Secondly, aspects concerning the sustainability of techniques, including the ones proposed in this thesis, deserve more attention. The long-term impact of reduced N input rates and the cumulative effect of organic N inputs, for instance, need clarification. Simulation models could be extremely helpful in improving our understanding of these aspects. Projections based on modelling will only be accepted, however, if the underlying assumptions are well-tested. After all, the financial implications for a farmer can be considerable. From this perspective there is an ongoing need for field experiments providing long time series of data.
Thirdly, techniques on the integration level of cropping systems need to be evaluated on the whole farm level too, as individual farm components may interact strongly. This is even more so in a mixed farm where all forages grown, must meet with the dietary requirements of the animals and where wastes must be recycled carefully. Reduced N inputs on maize land, for instance, may force dairy farmers to use more wastes on their grassland. Reduced N inputs on maize land may therefore have undesired effects on

the N emission from grassland or on the productivity of grassland. The dairy farm model developed by Van de Ven (1996) is a tool for making ideal combinations of crops and their production techniques under given constraints. It was run with the input-output coefficients available in 1995 and the conclusions may therefore have a limited life-span. It would be worth re-running this model every now and then, as our knowledge of cropping techniques and, hence, the coefficients, changes constantly.

9.5 Summing up

The results presented in this thesis show that cover crops and slurry and fertiliser placement can be promising techniques for the improvement of the recovery of N. This conclusion justifies reducing the amounts of N recommended for growing a high yielding maize crop. Without a reduction of the N input, neither cover crops nor placement contribute to the reduction of N losses, unless crops are N deficient. Consequently, decisions on the use of cover crops and N placement should always be integrated with decisions on slurry and fertiliser rates, to ensure that cover crops and N placement are really effective in reducing N emissions.

CONCLUSIONS

- Confinement of the application of N to only those parts of the soil profile where a high root length density is anticipated improves the recovery of N, reduces the losses of N and justifies a downward adjustment of N rates.

- The application of slurry in autumn does not become a reliable alternative for the application of slurry in spring by addition of a nitrification inhibitor.

- Postponement of the application of N until after crop emergence, does generally not improve the N use efficiency in maize.

- Cover crops grown after maize can reduce nitrate leaching by 40 kg N per ha and will contribute to the N supply available to subsequent crops.

- A downward adjustment of the N rate applied to maize has a large potential to reduce the adverse effect of N on the environment with a limited effect on silage yields.

- Fine-tuning of the N rate applied to maize is possible by accounting for site characteristics such as the native soil N supply, the manuring history and the N contributions from previous crops including cover crops.

- The reduction of the N surpluses imposed on farms by the anticipated MINAS-legislation, will be insufficient to yield a quality of the upper groundwater under maize land on dry sandy soils, that meets the EC Nitrate Directive for drinking water.

REFERENCES

Addiscott, T.M., 1983. Kinetics and temperature relationships of mineralization and nitrification in Rothamsted soils with differing histories. *Journal of Soil Science* 34: 343-353.

Addiscott, T.M. & D.S. Powlson, 1992. Partitioning losses of nitrogen fertilizer between leaching and denitrification. *Journal of Agricultural Science Cambridge* 118: 101-107.

Addiscott, T.M. & A.P. Whitmore, 1987. Computer simulation of changes in soil mineral nitrogen and crop nitrogen during autumn, winter and spring. *Journal of Agricultural Science Cambridge* 109: 141-157.

Amberger, A. 1986. Potentials of nitrification inhibitors in modern N fertilizer management. *Zeitschrift für Pflanzenernährung und Bodenkunde* 149: 469-484.

Anderson, E.L., 1988. Tillage and N fertilization effects on maize root growth and root:shoot ratio. *Plant and Soil* 108: 245-251.

Anonymous, 1971-1996. Annual publication of the list of recommended varieties of agricultural crops (In Dutch). CPRO-DLO, Wageningen, 320 pp - 354 pp.

Anonymous, 1980. European Economic Community Council Directive on the quality of water for human consumption. *Official Journal* 23, 80/778 EECL 229: 11-29.

Anonymous, 1981. A survey on the cropping technique of silage maize in Gelderland (In Dutch). Consulentschap voor Rundveehouderij en Akkerbouw, Tiel, 55 pp.

Anonymous, 1985. Animal manure (In Dutch). Brochure No. 406, Ministry of Agriculture and Fisheries, The Hague, 12 pp.

Anonymous, 1987. Facts and figures on agriculture 1987 (In Dutch). LEI-DLO/CBS, The Hague, 253 pp.

Anonymous, 1989. Fertilizer Recommendations for Grassland and Fodder crops (In Dutch). Consulentschap voor Bodem-, Water- en Bemestingszaken in de Veehouderij, Wageningen, 72 pp.

Anonymous, 1991. Facts and figures on agriculture 1991 (In Dutch). LEI-DLO/CBS, The Hague, 247 pp.

Anonymous, 1995. Integral note on manure and ammonia policy. Ministry of Housing, Physical Planning and Environment (VROM), The Hague, 35 pp.

Anonymous, 1996a. Facts and figures on agriculture 1996 (In Dutch). LEI-DLO/CBS, The Hague, 273 pp.

Anonymous, 1996b. Manure and ammonia policy (In Dutch). Newsletter, Ministry of Housing, Physical Planning and Environment (VROM), The Hague, 12 pp.

Asman, W.A.H., 1992. Ammonia emission in Europe: updated emission and emission variations. Report 228471008, RIVM, Bilthoven, 88 pp.

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

Aufhammer, W., E. Kübler & H.P. Kaul, 1996. Untersuchungen zur Anpassung des Stickstoff-Angebots aus unterschiedlichen N-Quellen an den Verlauf der N-Aufnahme von Maisbestanden. *Zeitschrift für Pflanzenernährung und Bodenkunde* 159: 471-478.

Bach, W., 1989. Growing consensus and challenge regarding a greenhouse climate. In: Climate and Food Security, IRRI, Los Baños, Philippines, 289-305.

Bacon, P.E. & J.A. Thompson, 1984. Effects of method and timing of nitrogen fertilizer application on irrigated maize growth and nutrient distribution in soil. *Australian Journal on Experimental Agriculture and Animal Husbandry* 24: 606-611.

Barber, S.A. & J.L. Kovar, 1991. Effect of tillage practice on maize root distribution. In: McMichel, B.L. & H. Persson (Eds.) Plant roots and their environment. Proceedings of an International Society on Root Research Symposium. August 21-26, Uppsala, Sweden. Elsevier, Amsterdam, 402-409.

Bassel, R., S. Müller & H. Görlitz, 1987. Operative Anpassung der N-Düngung zu Silomais durch Einbeziehung des anorganische Bodenstickstoffs. *Archiv für Acker- und Pflanzenbau und Bodenkunde Berlin* 31: 47-53.

Beauchamp, E.G., 1983 Response of corn to nitrogen in preplant and sidedress applications of liquid dairy cattle manure. *Canadian Journal of Soil Science* 63: 377-386.

Beauchamp, E.G. & R.G. Kachanoski, 1989. A N soil test for corn. *Annual Report 1988,* University of Guelph, 69-70.

Beijer, L. & H. Westhoek, 1996. Fertilizers for cattle farming (In Dutch). Publicatie 17, Informatie- en Kennis Centrum Landbouw, Ede, 109 pp.

Binford, G.D., A.M. Blackmer & M.E. Cerrato, 1992a. Relationships between corn yields and soil nitrate in late spring. *Agronomy Journal* 84: 53-59.

Binford, G.D., A.M. Blackmer & M.E. Cerrato, 1992b. Nitrogen concentration of young corn plants as an indicator of nitrogen availability. *Agronomy Journal* 84: 219-223.

Blackmer, A.M., T.F. Morris & G.D. Binford, 1992. Predicting N fertilizer needs in humid regions: advances in Iowa. In: Bock, B.R. & K.R. Kelley (Eds.) Predicting N Fertilizer Needs for Corn in Humid Regions: Soil Science Society of America, Denver, 57-72.

Blackmer, A.M., D. Pottker, M.E. Cerrato & J. Webb, 1989. Correlations between soil nitrate concentrations in late spring and corn yields in Iowa. *Journal of Production Agriculture* 2: 103-109.

Blaylock, A.D. & R.M. Cruse, 1992. Ridge-tillage corn response to point injected nitrogen fertilizer. *Soil Science Society of America Journal* 56: 591-595.

Bleeker, A., J.W. Erisman & J.M.M. Aben, 1994. Acidification and eutrophication. In: Aben, J. (Ed.) Air Quality Annual Report *1993* (In Dutch), RIVM, Bilthoven, pp. 35-41.

Boer, J., 1984. Factor analysis research on silage maize in Eastern Overijssel in 1981 and 1982 (In Dutch). Report 16, PAGV, Lelystad, 117 pp.

Bollero, G.A. & D.G. Bullock, 1994. Cover cropping systems for the Central Corn Belt. *Journal of Production Agriculture* 7: 55-58.

Booij, R., A.D.H. Kreuzer, A.L. Smit & A. Van Der Werf, 1996. Effect of nitrogen availability on dry matter production, nitrogen uptake and light interception of Brussels sprouts and leeks. *Netherlands Journal of Agricultural Science* 44: 3-19.

Bottner, P., Z. Mneimne & G. Billes, 1984. Réponse de la biomasse microbienne à l'adjonction au sol de matérial végétal marqué au ^{14}C: rôle des racines vivantes. *Soil Biology and Biochemistry* 16: 305-314.

Bullock, D.G. & D.S. Bullock, 1994. Quadratic and quadratic plus plateau models for predicting optimal nitrogen rate of corn: a comparison. *Agronomy Journal* 86: 191-195.

Bundy, L.G., T.W. Andraski & T.C. Daniel, 1992. Placement and timing of nitrogen fertilizers for conventional and conservation tillage corn production. *Journal of Production Agriculture* 5: 214-221.

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

Chakravarty, D.N. & R.M. Karmakar, 1980. Root development of different maize varieties in Diphu area of Assam. *Indian Journal of Agricultural Science* 50: 527-531.

Chaudhary, M.R. & S.S. Prihar, 1974. Root development and growth response of corn following mulching, cultivation or interrow compaction. *Agronomy Journal* 66: 350-355.

Clark, R.B., 1983. Plant genotype differences in the uptake, translocation, accumulation and use of mineral elements required for plant growth. *Plant and Soil* 72: 175-196.

Clarkson, D.T. & G.C. Gerloff, 1979. Plant nutrition and morphogenesis -the effect of temperature on root growth and mineral nutrition of young maize plants. Annual Report 1978. Letcombe Laboratory, Letcombe, Wantage, pp. 52-54.

Clay, D.E., C.C. Carlson, P.W. Holman, T.E. Schumacher & S.A. Clay, 1995. Banding nitrogen fertilizer influence on inorganic nitrogen distribution. *Journal of Plant Nutrition* 18: 331-341.

De Vos, J.A., 1997. Water flow and nutrient transport in a layered silt loam soil. PhD Thesis Wageningen Agricultural University, 287 pp.

De Willigen, P. & M. Van Noordwijk, 1987. Roots, plant production and nutrient use efficiency. PhD Thesis Wageningen Agricultural University, 282 pp.

De Willigen, P. & M. Van Noordwijk, 1995. Model for interactions between water and nutrient uptake. In: Kabat, P., 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.

De Willigen, P., W.P. Wadman & M. Van Noordwijk, 1992. Model calculations on the risks of accumulation of residual soil mineral N (In Dutch). In: Van Der Meer, H.G. & J.H.J. Spiertz (Eds.) Stikstofstromen in agro-ecosystemen. Agrobiologische Thema's 6, CABO-DLO, Wageningen, 87-101.

De Wit, C.T., 1953. A physical theory on placement of fertilizers. Verslagen van Landbouwkundige Onderzoekingen No. 59. Staatsdrukkerij, The Hague, 71 pp.

De Wit, C.T., 1992. Resource use efficiency. *Agricultural Systems* 40: 125-151.

Dilz, K., A. Darwinkel, R. Boon & L.M.J. Verstraeten, 1982. Intensive wheat production as related to nitrogen fertilisation, crop production and soil nitrogen: experience in the Benelux. Proceedings 211, The Fertiliser Society, London, 93-124.

Dilz, K., J. Postmus & W.H. Prins, 1990. Residual effect of long-term application of farmyard manure to silage maize. *Fertilizer Research* 26: 249-252.

Döhler, H., 1991. Laboratory and field experiments for estimating ammonia losses from pig and cattle slurry following application. In: Nielsen, V.C., J.H. Voorburg & P. L'Hermite (Eds.) Odour and Ammonia Emissions from Livestock Farming, Elsevier, London, 132-144.

Eckert, D.J., 1987. UAN management practices for no-tillage corn production. *Journal of Fertilizer Issues* 4: 13-18.

Eghball, B. & J.W. Maranville, 1993. Root development and nitrogen influx of corn genotypes grown under combined drought and nitrogen stresses. *Agronomy Journal* 85: 147-152.

Elers, B. & H.D. Hartmann, 1988. Modellversuche zur Mineralisation von Gründüngungspflanzen. *Landwirtschaftliche Forschung* 41: 3-4.

Ellies, A. & A. Huber, 1991. Wasserhaushalt und Bodenwasserverteilung bei einer Futtermaiskultur in Südchile. *Zeitschrift für Pflanzenernährung und Bodenkunde* 154: 9-12.

Engels, Ch. & H. Marschner, 1990. Effect of sub-optimal root zone temperatures at varied nutrient supply and shoot meristem temperature on growth and nutrient concentrations in maize seedlings. *Plant and Soil* 126: 215-225.

Erisman, J.W. & G.J. Heij, 1991. Concentration and deposition of acidifying compounds. In: Heij, G.J. & T. Schneider (Eds.), Acidification in The Netherlands. Studies in Environmental Science 46, Elsevier, Amsterdam, pp. 51-96.

Evanylo, G.K., 1991. No-till response to nitrogen rate and timing in the middle atlantic coastal plain. *Journal of Production Agriculture* 4: 180-185.

Foth, H.D., 1962. Root and top growth of corn. *Agronomy Journal* 54: 49-52.

Fox, R.H., G.W. Roth, K.V. Iversen & W.P. Piekielek, 1989. Soil and tissue nitrate tests compared for predicting soil nitrogen availability to corn. *Agronomy Journal* 81: 971-974.

Gascho, G.J. & J.E. Hook, 1991. Development of a fertigation program for sprinkler-irrigated corn. *Journal of Production Agriculture* 3: 306-312.

Girardin, Ph., 1992. The funnel effect of a maize canopy. Proceedings of the 2nd European Society of Agronomy Congress, ESA, Colmar, pp. 76-77.

Goodroad, L.L. & M.D. Jellum, 1988. Effect of N fertilizer rate soil pH on N efficiency in corn. *Plant and Soil* 106: 85-89.

Goossensen, F.R. & P.C. Meeuwissen, 1990. Recommendations of the Nitrogen Committee (In Dutch). DLO, Wageningen, 93 pp.

Görlitz, H., 1989. Verringerung der N-Verlagerung im Boden nach Gülledüngung durch Einsatz von Nitrifikationsinhibitoren; Ergebnisse aus Lysimeteruntersuchungen. *Archiv für Acker- und Pflanzenbau und Bodenkunde, Berlin* 33: 567-572.

Görlitz, H., V. Herrmann & R. Jauert, 1985. Ertrag und Nährstoffnutzung nach ein- und mehrjährigen hohen Güllegaben zu Silomais sowie ihre Nachwirkung auf sandigen Böden. *Archiv für Acker- und Pflanzenbau und Bodenkunde Berlin* 29: 55-60.

Granato, T.C. & C.D. Raper, 1989. Proliferation of maize roots in response to localized supply of nitrate. *Journal of Experimental Botany* 40: 263-275.

Greenwood, D.J., K. Kubo, I.G. Burns & A. Draycott, 1989. Apparent recovery of fertilizer-N by vegetable crops. *Soil Science and Plant Nutrition* 35: 367-381.

Greenwood, D.J., J.J. Neeteson & A. Draycott, 1985. Response of potatoes to N fertilizer; quantitative relations for components of growth. *Plant and Soil* 85: 163-183.

Greenwood, D.J., J.J. Neeteson, A., Draycott, G. Wijnen & D.A. Stone, 1992. Measurement and simulation of the effect of N-fertilizer on growth, plant composition and distribution of soil mineral-N in nationwide onion experiments. *Fertilizer Research* 33: 305-318.

Grobbelaar, W.P., 1963. Responses of young maize plants to root temperatures. *Mededelingen van de Landbouwhogeschool* 63, Wageningen, 71 pp.

Guenzi, W.D., W.E. Beard, F.S. Watanabe, S.R. Olsen & L.K. Porter, 1978. Nitrification and denitrification in cattle manure amended soil. *Journal of Environmental Quality* 7: 196-202.

Hanway, J.J., 1962. Corn growth and composition in relation to soil fertility. II Uptake of N, P and K and their distribution in different plant parts during the growing season. *Agronomy Journal* 54: 217-222.

Hauck, R.D., 1980. Mode of action of nitrification inhibitors. In: Meisinger, J.J., G.W. Randall & M.L. Vitosh (Eds.) Nitrification inhibitors, potentials and limitations. American Society of Agronomy, Madison, 19-31.

Heinen, M., 1997. Dynamics of water and nutrients in closed, recirculating cropping systems in glasshouse horticulture, PhD Thesis Wageningen Agricultural University, 270 pp.

Iversen, K.V., R.H. Fox & W.P. Piekielek, 1985a. Diurnal, shade and hybrid effects on nitrate content of young corn stalks. *Communications in Soil Science and Plant Analysis* 16: 837-852.

Iversen, K.V., R.H. Fox & W.P. Piekielek, 1985b. The relationships of nitrate concentrations in young corn stalks to soil nitrogen availability and grain yields. *Agronomy Journal* 77: 927-932.

Jackson, L.E., L.J. Wyland & L.J. Stivers, 1993. Winter cover crops to minimize nitrate losses in intensive lettuce production. *Journal of Agricultural Science Cambridge* 121: 55-62.

Jokela, W.E., 1992a. Nitrogen fertilizer and dairy manure effects on corn yield and soil nitrate. *Soil Science Society of America Journal* 56: 148-154.

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

Jokela, W.E. & G.W. Randall, 1989. Corn yield and residual nitrate as affected by time and rate of nitrogen application. *Agronomy Journal* 81: 720-726.

Jones, C.A. & J.R. Kiniry, 1986. CERES-maize: a simulation model of maize growth and development. Texas A&M Univ. Press, College Station, 194 pp.

Karlen, D.L., R.L. Flannery & E.J. Sadler, 1988. Aerial accumulation and partitioning of nutrients by corn. *Agronomy Journal* 80: 232-242.

Ketcheson, J.W., 1968. Effects of controlled air and soil temperature and starter fertilizer on growth and nutrient composition of corn (*Zea mays* L.). *Soil Science Society of America Proceedings* 32: 531-534.

Keuning, J., 1984. Swad height meter: an aid for estimating the amount of grass (In Dutch). Jaarverslag 1983. Research Station for Cattle, Sheep and Horse Husbandry, Lelystad, pp. 19-22.

Kiel, C. & P. Stamp, 1992. Internal root anatomy of maize seedlings (*Zea mays* L.) as influenced by temperature and genotype. *Annals of Botany* 70: 125-128.

Kiesselbach, T.A., 1949. The structure and reproduction of corn. Research Bulletin 161. Agricultural Experimental Station, University of Nebraska, 96 pp.

Killorn, R. & D. Zourakis, 1992. Nitrogen fertilizer management effects on corn grain yield and nitrogen uptake. *Journal of Production Agriculture* 1: 142-148.

Klausner, S.D., W.S. Reid & D.R. Bouldin, 1993. Relationship between late spring soil nitrate concentrations and corn yields in New York. *Journal of Production Agriculture* 6: 350-354.

Korevaar, H. & D.J. Den Boer, 1990. Practical measures to reduce nutrient losses from grassland systems. Proceedings 301, The Fertiliser Society, London, 33 pp.

Kortleven, J., 1963. Quantitative aspects of humus build-up and humus decomposition (In Dutch). *Verslagen van Landbouwkundig Onderzoek* 69-1, Pudoc, Wageningen, 109 pp.

Kuchenbuch, R.O. & S.A. Barber, 1988. Significance of temperature and precipitation for maize root distribution in the field. *Plant and Soil* 106: 9-14.

Ladewig, E. & B. Märländer, 1997. Determination of optimum N-supply in sugar beet by different mathematical methods. *Zeitschrift für Pflanzenernährung und Bodenkunde* 160: 85-88.

Lang, H., 1978. Beregnung sichert den Maisertrag. *Mais-DMK* 2: 40-44.

Lang, A.R.G. & F.M. Melhuish, 1970. Lengths and diameters of plant roots in non-random populations by analysis of plane surfaces. *Biometrics* 26: 421-431.

Laurent, F. & B. Mary, 1992. Management of nitrogen in farming systems and the prevention of nitrate leaching. *Aspects of Applied Biology* 30: 45-61.

Legg, J.O., G. Stanford & O.L. Bennett, 1979. Utilization of labeled N fertilizer by silage corn under conventional and not-till culture. *Agronomy Journal* 71: 1009-1015.

Liang, B.C. & A.F. Mackenzie, 1992. Changes in soil organic carbon and nitrogen after six years of corn production. *Soil Science* 153: 307-313.

Lorenz, F., 1992. Gülledüngung mit ergänzenden Mineral N Gaben zur Erzielung optimaler Erträge bei niedrigem Nitrataustrag. *Göttinger Bodenkundliche Berichte* 99. Institut für Bodenwissenschaft, Göttingen, 172 pp.

Lory, J.A., M.P. Russelle & T.A. Peterson, 1995. A comparison of two nitrogen credit methods: traditional vs. difference. *Agronomy Journal* 87: 648-651.

Lund, Z.F. & B.D. Doss, 1980; Residual effects of dairy cattle manure on plant growth and soil properties. *Agronomy Journal* 72: 123-130.

Mackay, A.D. & S.A. Barber, 1984. Soil temperature effects on root growth and phosphorus uptake by corn. *Soil Science Society of America Journal* 48: 818-823.

MacKenzie, A.F., L.E. Phillip & P.C. Kirby, 1988. Effect of added urea and potassium chloride on yields of corn over four years and on soil potassium. *Agronomy Journal* 80: 773-777.

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.

Magdoff, F.R., 1991. Understanding the Magdoff pre-sidedress nitrate test for corn. *Journal of Production Agriculture* 4: 297-305.

Magdoff, F.R. & J.F. Amadon, 1980. Yield trends and soil chemical changes resulting from N and manure application to continuous corn. *Agronomy Journal* 72: 161-164.

Magdoff, F.R., D. Ross & J. Amadon, 1984. A soil test for nitrogen availability to corn. *Soil Science Society of America Journal* 48: 1301-1304.

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

Martinez, J. & G. Guiraud, 1990. A lysimeter study of the effects of a ryegrass catch crop, during a winter wheat/maize rotation, on nitrate leaching and on the following crop. *Journal of Soil Science* 94: 5-16.

McCracken, D.V., M.S. Smith, J.H. Grove, C.T. MacKown & R.L. Blevins, 1994. Nitrate leaching as influenced by cover cropping and nitrogen source. *Soil Science Society of America Journal* 58: 1476-1483.

Meijboom, F. & M. Van Noordwijk, 1992. Rhizon soil solution samplers as artificial roots. In: Kutschera, L., E. Hübl, E. Lichtenegger, H. Persson & M. Sobotik (Eds.) Root ecology and its applications. Verein für Wurzelforschung, Klagenfurt, 793-795.

Meisinger, J.J., V.A. Bandel, G. Stanford & J.O. Legg, 1985. Nitrogen utilization of corn under minimal tillage and moldboard plow tillage. I. Four year results using labeled N fertilizer on an Atlantic coastal plain soil. *Agronomy Journal* 77: 602-611.

Melhuish, F.M. & A.R.G. Lang, 1968. Quantitative studies of roots in soil. I. Length and diameters of cotton roots in a clay-loam soil by analysis of surface-ground blocks of resin-impregnated soil. *Soil Science* 106: 16-22.

Menelik, G., R.B. Reneau & D.C. Martens, 1994. Corn yield and nitrogen uptake as influenced by tillage and applied nitrogen. *Journal of Plant Nutrition* 17: 911-931.

Mengel, D.B. & S.A. Barber, 1974. Development and distribution of the corn root system under field conditions. *Agronomy Journal* 66: 341-344.

Miedema, P., 1982. The effects of low temperature on *Zea mays*. *Advances in Agronomy* 35:93-128.

Montgomery, D.C. & E.A. Peck, 1982. Introduction to linear regression analysis. Wiley and Sons, New York, 504 pp.

Motavalli, P.P. L.G. Bundy, T.W. Andraski & A.E. Peterson, 1992. Residual effects of long-term nitrogen fertilization on nitrogen availability to corn. *Journal of Production Agriculture* 5: 363-368.

Muchow, R.C., 1988. Effect of nitrogen supply on the comparative productivity of maize and sorghum in a semi-arid tropical environment. I. Leaf growth and leaf nitrogen. *Field Crops Research* 18: 1-16.

Muchow, R.C. & R. Davis, 1988. Effect of nitrogen supply on the comparative productivity of maize and sorghum in a semi-arid tropical environment. II. Radiation interception and biomass accumulation. *Field Crops Research* 18: 17-30.

Neeteson, J.J., 1989a. Evaluation of the performance of three advisory methods for nitrogen fertilization of sugar beets and potatoes. *Netherlands Journal of Agricultural Science* 37: 143-155.

Neeteson, J.J., 1989b. Assessment of fertilizer nitrogen requirement of potatoes and sugar beet. PhD Thesis Wageningen Agricultural University, 141 pp.

Neeteson, J.J., 1994. Residual soil nitrate after application of nitrogen fertilizers to crops. In: Adriano, D.C., A.K. Iskandar & I.P. Murarka (Eds.) Contamination of groundwaters. Advances in Environmental Science, Science Reviews, Northwood, United Kingdom, 347-365.

Neeteson, J.J., 1995. Nitrogen management for intensively grown arable crops and field vegetables. In: Bacon, P.E. (Ed.). Nitrogen fertilization and the environment. Marcel Dekker Inc., New York, 295-325.

Neeteson, J.J. & W.P. Wadman, 1987. Assessment of economically optimum application rates of fertilizer N on the basis of response curves. *Fertilizer Research* 12: 37-52.

Neeteson, J.J., D.J. Greenwood, & A. Draycott, 1987. A dynamic model to predict yield and optimum nitrogen fertiliser application rate for potatoes. Proceedings 262, The Fertiliser Society, London, 31 pp.

Oenema, O., P.C.M., Boers, M.M. Van Eerdt, B. Fraters, H.G. Van Der Meer, C.W.J. Roest, J.J. Schröder & W.J. Willems, 1997. The nitrate problem and nitrate policy in The Netherlands: evaluation of the nitrogen accounting system MINAS. Nota 88, AB-DLO, Haren, 21 pp.

Onken, A.B., R.L. Matheson & D.M. Nesmith, 1985. Fertilizer nitrogen and residual nitrate nitrogen effects on irrigated corn. *Soil Science Society of America Journal* 49: 134-139.

Osmond, D.L., D.J. Lathwell & S.J. Riha, 1992. Prediction of long-term fertilizer nitrogen requirements of maize in the tropics using a nitrogen balance model. *Plant and Soil* 143: 61-70.

O'Toole, J.C. & W.L. Bland, 1987. Genotypic variation in crop plant root systems. *Advances in Agronomy* 41, Academic Press, New York, pp. 91-145.

Pollmer, W.G., D. Eberhard, D. Klein & B.S. Dhillon, 1979. Genetic control of nitrogen uptake and translocation in maize. *Crop Science* 19: 83-86.

Primost, E., 1964. Ertrag und Qualität von Silomais in Abhängigkeit von der Stickstoffdüngung und der Witterung. *Das Wirtschaftseigene Futter* 10: 10-22.

Prins, W.H. & P.J.M. Snijders, 1987. Negative effects of animal manure on grassland due to surface spreading and injection. In: Van der Meer, H.G., R.J. Unwin, T.A. Van Dijk & G.C. Ennik (Eds.), Animal Manure on Grassland and Fodder Crops. Martinus Nijhoff Publishers, Dordrecht, pp. 119-135.

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 276, The Fertiliser Society, London, 27 pp.

Prummel, J., 1957. Fertilizer placement experiments. *Plant and Soil* 8: 231-253.

Rao, A.C.S., J.L. Smith, J.F. Parr & R.I. Papendick, 1992. Considerations in estimating nitrogen recovery efficiency by the difference and isotopic dilution methods. *Fertilizer Research* 33: 209-217.

Reeves, D.W. & J.T. Touchton, 1986. Effects of in-row and interrow subsoiling and time of nitrogen application on growth, stomatal conductance and yield of strip-tilled corn. *Soil Tillage Research* 7: 327-340.

Reeves, D.W., C.W. Wood & J.T. Touchton, 1993. Timing nitrogen applications for corn in a winter legume conservation-tillage system. *Agronomy Journal* 85: 98-106.

Renius, W. & E. Lütke Entrup, 1985. Zwischenfruchtbau; zur Futtergewinnung und Gründüngung. DLG Verlag, Frankfurt am Main, 196 pp.

Rice, C.W., P.E. Sierzega, M. Tiedje & L.W. Jacobs, 1988. Stimulated denitrification in the microenvironment of a biodegradable organic waste injected into soil. *Soil Science Society of America Journal* 52: 102-108.

Richner, W., 1992. Wurzelwachstum junger Maispflanzen in Abhängigkeit von der Temperatur. Dissertation ETH, Zürich, 107 pp.

Russelle, M.P., E.J. Deibert, R.D. Hauck, M. Stevanovic & R.A. Olsen, 1981. Effects of water and nitrogen management on yield and 15N depleted fertilizer use efficiency of irrigated corn. *Soil Science Society of America Journal* 75: 593-598.

Salardini, A.A., L.A. Sparrow & R.J. Holloway, 1992. Sweet corn response to basal and top-dressed rates and sources of nitrogen fertilizers. *Australian Journal of Agricultural Research* 43: 171-180.

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 of Production Agriculture* 3: 335-344.

Scaglia, J., R. Lensi & A. Chalamet, 1985. Relationship between photosynthesis and denitrification in planted soil. *Plant and Soil* 84: 37-43.

Schapendonk, A.H.C.M., C.S. Pot, D.W.G. Van Kraalingen & O. Dolstra, 1994. Effect of low temperature on photosynthetic control in maize. In: Dörffling, K., B. Brettschneider, H. Tantau & K. Pithan (Eds.) Crop adaptation to cool climates: Cost 814, October 12-14, 1994, Hamburg, 553-560.

Schlegel, A.J. & J.L. Havlin, 1995. Corn response to long-term nitrogen and phosphorus fertilization. *Journal of Production Agriculture* 8: 181-185.

Schlegel, A.J., K.C. Dhuyvetter & J.L. Havlin, 1996. Economic and environmental impacts of long-term nitrogen and phosphorus fertilization. *Journal of Production Agriculture* 9: 114-118.

Schmitt, M.A. & G.W. Randall, 1994. Developing a soil nitrogen test for improved recommendations for corn. *Journal of Production Agriculture* 7: 328-334.

Schneider, C.B.H. & P.J.M. Van Boheemen, 1986. Rules for soil moisture budgetting (In Dutch). *De Buffer* 3/4: 84-117.

Scholte, K., 1987. Relationship between cropping frequency, root rot and yield of silage maize on sandy soils. *Netherlands Journal of Agricultural Science* 35: 473-486.

Scholte, K. & J.J. s' Jacob, 1983. Significance of continuous cropping and free-living root nematodes for the yield of silage maize (In Dutch). Verslag 6, PAGV, Lelystad, 12-23.

Schröder, J.J., 1985a. The effect of heavy cattle slurry applications on growth, yield and quality of fodder maize and on soil fertility and groundwater pollution; Maarheeze 1974-1982 (In Dutch). Verslag 31, PAGV, Lelystad, 101 pp.

Schröder, J.J., 1985b. Effects of heavy cattle slurry applications on growth, yield and quality of silage maize and on soil fertility: Heino (sandy soil) 1972-1982 (In Dutch). Verslag 30, PAGV, Lelystad, 151 pp.

Schröder, J.J., 1985c. Effects of heavy cattle slurry applications on growth, yield and quality of silage maize and on soil fertility: Lelystad (clay soil) 1976-1980 (In Dutch). Verslag 32, PAGV, Lelystad, 101 pp.

Schröder, J.J, 1990a. Split N applications in maize (In Dutch). Verslag 106, PAGV, Lelystad, 104 pp.

Schröder, J.J., 1990b. Nitrogen losses with maize cropping (In Dutch). *Meststoffen* 1/2: 25-32.

Schröder, J.J., 1990c. Maize and manure: from tolerance towards utilization (In Dutch). Themaboekje 10, PAGV, Lelystad, 86-96.

Schröder, J.J., 1997. Effect of split applications of cattle slurry and mineral fertilizer N on the yield of silage maize in a slurry-based cropping system. *Nutrient Cycling in Agroecosystems* (in press).

Schröder, J.J. & K. Dilz, 1987. Cattle slurry and farmyard manure as fertilizers for forage maize. In: Van Der Meer, H.G., R.J. Unwin, T.A. Van Dijk & G.C. Ennik (Eds.) *Animal manure on grassland and fodder crops*. Martinus Nijhoff Publishers, Dordrecht, 137-156.

Schröder, J.J. & L. Ten Holte, 1993. Effects of nitrification inhibitors, application time and rate of mineral fertilizer N and slurry on yields of silage maize and losses to the environment (In Dutch). Verslag 179, CABO-DLO, Wageningen, 52 pp.

Schröder, J.J. & L. Ten Holte, 1995. Effects of manure placement on silage maize. In: Hall J., (Ed.), REUR Technical Series 34, FAO, Rome, pp. 183-189.

Schröder, J.J. & L. Ten Holte, 1996. Fertilizer trials in maize and forage beet crops at the experimental farm for integrated dairy farming De Marke (In Dutch). Rapport 63, AB-DLO, Wageningen, 39 pp.

Schröder, J.J. & W. Van Dijk, 1995. Growing maize with a limited loss of nutrients (In Dutch). Themaboekje 19, PAGV, Lelystad, 12-37.

Schröder, J.J. & H. Van Keulen, 1997. Modelling the residual N effect of large slurry applications on maize land in The Netherlands. *Netherlands Journal of Agricultural Science* 45(4) (in press).

Schröder, J.J., L. Ten Holte, W. Van Dijk, W.J.M. De Groot, W.A. De Boer & E.J. Jansen, 1992a. Effects of cover crops on N leaching in maize cropping system (In Dutch). Verslag 148. Research Station for Arable Farming and Field Production of Vegetables, Lelystad, 105 pp.

Schröder, J.J., W.J.M. De Groot & W. Van Dijk, 1992b. Nitrogen losses from continuous maize as affected by cover crops. In: Archer, J.R., K.W.T. Goulding, S.C. Jarvis, C.M. Knott, E. Lord, S.E. Ogilvy, J. Orson, K.A. Smith, & B. Wilson, (Eds.) Nitrate and Farming Systems. *Aspects of Applied Biology* 30: 317-326.

Schröder, J.J., L. Ten Holte, H. Van Keulen & J.H.A.M. Steenvoorden, 1993. Effects of nitrification inhibitors and time and rate of slurry and fertilizer N application on silage maize yield and losses to the environment. *Fertilizer Research* 34: 267-277.

Schröder, J.J., J. Groenwold & T. Zaharieva, 1994. Root growth and development of maize during the juvenile stage- rhizolab experiments in 1992 and 1993. Report 20, AB-DLO, Wageningen, 64 pp.

Schröder, J.J., L. Ten Holte & G. Brouwer, 1995. Row application of slurry (In Dutch). Rapport 44. AB-DLO, Wageningen, 46 pp.

Schröder, J.J., J. Groenwold & T. Zaharieva, 1996a. 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., W. Van Dijk & W.J.M. De Groot, 1996b. Effects of cover crops on the nitrogen fluxes in a silage maize production system. *Netherlands Journal of Agricultural Science* 44: 293-315.

Schröder, J.J., P. Van Asperen, G.J.M. Van Dongen & F.G. Wijnands, 1996c. Nutrient surpluses on integrated arable farms. *European Journal of Agronomy* 5: 181-191.

Schröder, J.J., L. Ten Holte & B.H. Janssen, 1997a. Non-overwintering cover crops: a significant source of N. *Netherlands Journal of Agricultural Science* 45: 231-248.

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

Schröder, J.J., J.J. Neeteson, J.C.M. Withagen & I.G.A.M. Noij, 1998. Effects of N application on agronomic and environmental parameters in silage maize production on sandy soils. Field Crops Research (accepted).

Schweiger, W., 1967. Ertrag und Entwicklungsverschiebung bei Futterroggen in Abhängigkeit von Saatzeit und Höhe der Stickstoffdüngung. *Albrecht Thär Archiv* 11: 775-784.

Scott, T.W., J. Mt. Pleasant, R.F. Burt & D.J. Otis, 1987. Contributions of ground cover, dry matter and nitrogen from intercrops and cover crops in a corn polyculture system. *Agronomy Journal* 79: 792-798.

Shaviv, A. & J. Hagin, 1991. Interaction of root distribution of corn with fertilizer placement and frequency of irrigation in lysimeters. *Fertilizer Research* 28: 49-54.

Shipley, P.R., J.J. Meisinger & A.M Decker, 1992. Conserving residual fertilizer nitrogen with winter cover crops. *Agronomy Journal* 84: 869-876.

Sinclair, T.R., 1990. Nitrogen influence on the physiology of the crop. In: Rabbinge, R., J. Goudriaan, H. van Keulen, F.W.T. Penning de Vries & H.H. van Laar (Eds.). *Theoretical Production Ecology: reflections and prospects.* Simulation Monographs 34, Pudoc, Wageningen, 41-55.

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: 483-486.

Sluijsmans, C.M.J. & G.J. Kolenbrander, 1977. The significance of animal manure in soils. In: Proceedings International Seminar Soil, Environment and Fertilizer Management in Intensive Agriculture, Society of the Science of Soil and Manure, Tokyo, pp. 403-411.

Smit. A.L., J. Groenwold & J. Vos, 1994. The Wageningen Rhizolab - a facility to study soil-root-shoot-atmosphere interactions in crops. II Methods of root observations. *Plant and Soil* 161: 289-298.

Solansky, S., 1981. SKW-Didin Stickstoffstabilisator; Versuchsergebnisse und Anwendungsempfehlungen. *Bayerisches Landwirtschaftliches Jahrbuch* 7: 879-891.

Sommerfeldt, T.G., C. Chang & T. Entz, 1988. Long-term annual manure applications increase soil organic matter and nitrogen, and decrease carbon to nitrogen ratio. *Soil Science Society of America Journal* 52: 1668-1672.

Stecker, J.A., D.D. Buchholz, R.G. Hanson, N.C. Wollenhaupt & K.A. McVay, 1995. Tillage and rotation effects on corn yield response to fertilizer nitrogen on aqualf soils. *Agronomy Journal* 87: 409-415.

Steffens, G. & H. Vetter, 1984. Stickstoffverlagerung nach Gülledüngung mit und ohne Zwischenfruchtanbau. *Landwirschaftliche Forschung Sonderheft* 40: 355-362.

Stemann, G. & N. Lütke Entrup, 1991. Umweltgerechter Anbau von Mais ist kein Problem. *Mais-DMK* 2/91: 25-29.

Stokes, D.T., R.K. Scott, C.H. Tilston, G. Cowie & R. Sylvester-Bradley, 1992. The effect of time of soil disturbance on nitrate mineralisation. *Aspects of Applied Biology* 30: 279-282.

Struik, P.C., 1983. Physiology of forage maize (*Zea mays* L.) in relation to its production and quality. PhD Thesis Wageningen Agricultural University, 252 pp.

Sylvester-Bradley, R., T.M. Addiscott, L.V. Vaidyanathan, A.W.A. Murray & A.P. Whitmore, 1987. Nitrogen advice for cereals: present realities and future possibilities. Proceedings No 263, The Fertiliser Society, London, 36 pp.

Tardieu, F. & S. Pellerin, 1991. Influence of soil temperature during root appearance on the trajectory of nodal roots of field grown maize. *Plant and Soil* 131: 207-214.

Tennant, D., 1975. A test of a modified line intersect method estimating root length. *Journal of Ecology* 63: 995-1001.

Thom, E.R. & B.R. Watkin, 1978. Effect of rate and time of fertiliser nitrogen application on total plant, shoot and root yields of maize. *New Zealand Journal of Experimental Agriculture* 6: 29-38.

Thorup-Kristensen, K., 1994. The effect of nitrogen catch crop species on the nitrogen nutrition of succeeding crops. *Fertilizer Research* 37: 227-234.

Timmons, D.R. & J.L. Baker, 1991. Recovery of point-injected labeled nitrogen by corn as affected by timing, rate and tillage. *Agronomy Journal* 83: 850-857.

Timmons, D.R. & J.L. Baker, 1992. Fertilizer management effects on recovery of labeled nitrogen by continuous no-till. *Agronomy Journal* 84: 490-496.

Torbert, H.A., R.G. Hoeft, R.M. Vanden Heuvel, R.L. Mulvaney & S.E. Hollinger, 1993. Short term excess water impact on corn yield and nitrogen recovery. *Journal of Production Agriculture* 6: 337-344.

Torbert, H.A., R.L. Mulvaney, R.M. Vanden Heuvel & R.G. Hoeft, 1992. Soil type and moisture regime effects on fertilizer efficiency calculation methods in a nitrogen 15 tracer study. *Agronomy Journal* 84: 66-70.

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

Trolldenier, G., 1989. Plant nutritional and soil factors in relation to microbial activity in the rhizosphere, with particular emphasis on denitrification. *Zeitschrift für Pflanzenernährung und Bodenkunde* 152: 223-230.

Van De Geijn, S.C., J. Vos, J. Groenwold, J. Goudriaan & P.A. Leffelaar, 1994. The Wageningen Rhizolab - a facility to study soil-root-shoot-atmosphere interactions in crops. I. Description of main functions. *Plant and Soil* 161: 275-287.

Van De Ven, G.W., 1996. A mathematical approach to comparing environmental and economic goals in dairy farming on sandy soils in The Netherlands. PhD Thesis Wageningen Agricultural University, 239 pp.

Van Der Eerden, L.J., W. De Vries, P. De Visser, H. Van Dobben, E.Steingröver, T. Dueck, H. Van Grinsven, F. Mohren, D. Boxman, J. Roelofs & J. Graveland, 1997. Effects on forest ecosystems. In: Heij, G.J. & J.W. Erisman (Eds.) Acid atmospheric deposition and its effects on terrestrial ecosystems in The Netherlands. Elsevier, Amsterdam, pp. 83-128.

Van Dijk, T.A., 1985. Leaching of plant nutrients from arable land as affected by annual applications of cattle slurry (In Dutch). Rapport 2-85, Institute for Soil Fertility, Haren, 61 pp.

Van Dijk, W., 1996. Effect of subsurface banding of N fertilizer on dry matter yield and N utilization of silage maize (In Dutch). Verslag 215. PAGV, Lelystad, 76 pp.

Van Dijk, T.A. & H. Sturm, 1983. Fertiliser value of animal manures on the continent. Proceedings 220, The Fertiliser Society, London, 45 pp.

Van Dijk, W., T. Baan Hofman, K. Nijssen, H. Everts, A.P. Wouters, J.G. Lamers, J. Alblas & J. Van Bezooijen, 1996. Effect of crop rotation of maize and grass (In Dutch). Verslag 217, PAGV, Lelystad, 140 pp.

Van Duijvenbooden, W. (Ed.), 1989. The quality of ground water in The Netherlands (In Dutch). Rapport 728820001, RIVM, Bilthoven, 307 pp.

Van Keulen, H., 1986. Crop yield and nutrient requirements. In: Van Keulen, H. & J. Wolf (Eds.) Modelling of agricultural production: weather, soils and crops. Simulation Monographs. Pudoc, Wageningen, 155-200.

Van Keulen, H. & W. Stol, 1990. Quantitative aspects of nitrogen nutrition in crops. *Fertilizer Research* 27: 151-160.

Van Noordwijk, M. & W.P. Wadman, 1992. Effects of spatial variability of nitrogen supply on environmentally acceptable fertilizer application rates to arable crops. *Netherlands Journal of Agricultural Science* 40: 51-72.

Van Swinderen, E.C., B. Fraters, H.A. Vissenberg, T. De Haan & D.W. De Hoop, 1996. Monitoring program of the quality of the upper groundwater on farms (In Dutch). Report 714831001, RIVM, Bilthoven, 90 pp.

Van Vuuren, A.M., C.J. Van Der Koelen, H. Valk & H. De Visser, 1993. Effects of partial replacement of ryegrass by low protein feeds on rumen fermentation and nitrogen loss by dairy cows. *Journal of Dairy Science* 76: 2982-2993.

Vanotti, M.B. & L.G. Bundy, 1994a. An alternative rationale for corn nitrogen fertilizer recommendations. *Journal of Production Agriculture* 7: 243-249.

Vanotti, M.B. & L.G. Bundy, 1994b. Corn nitrogen recommendations based on yield response data. *Journal of Production Agriculture* 7: 249-256.

Varvel, G.E. & T.A. Peterson, 1990. Nitrogen fertilizer recovery by corn in monoculture and rotation systems. *Agronomy Journal* 82: 935-938.

Vilsmeier, K. & A. Amberger, 1987. Zur nitrifikationshemmenden Wirkung von Dicyandiamid zu Gülle in der Zeit zwischen Spätherbst und Frühjahr. *Zeitschrift für Pflanzenernährung und Bodenkunde* 150: 47-50.

Vos, G.J.M., I.M.J. Bergevoet, J.C. Védy & J.A. Neyroud, 1994. The fate of spring applied fertilizer N during the autumn-winter period: comparison between winter-fallow and green manure cropped soil. *Plant and Soil* 160: 201-213.

Wagger, M.G., 1989a. Time of desiccation effects on residue composition and subsequent nitrogen release from several winter annual cover crops. *Agronomy Journal* 81: 236-241.

Wagger, M.G., 1989b. Cover crop management and nitrogen rate in relation to growth and yield of no-till corn. *Agronomy Journal* 81: 533-538.

Walker, J.M., 1969. One-degree increments in soil temperatures affect maize seedlings behavior. *Soil Science Society of America Proceedings* 33: 729-736.

Walther, U. & F. Jäggli, 1989. Pflanzen- und Umweltgerechte Stickstoffdüngung des Maises. *Mais-DMK* 2: 18-21.

Wantulla, A., F.J. Vollmer & W. Kühbauch, 1988. Einfluss von Düngungsmassnahmen auf die Stickstoffauswaschung bei mehrjährigem Silomaisanbau. *Zeitschrift für Pflanzenernährung und Bodenkunde* 151: 97-102.

Wehrmann, J. & H.C. Scharpf, 1986. The Nmin-method - an aid to integrating various objectives of nitrogen fertilization. *Zeitschrift für Pflanzenernährung und Bodenkunde* 149: 428-440.

Welch, L.F., D.L. Mulvaney, M.G. Oldham, L.V. Boone & J.W. Pendleton, 1971. Corn yields with fall, spring and sidedress nitrogen. *Agronomy Journal* 63: 119-123.

Wellbank, P.J., M.J. Gibb, P.J. Taylor & E.D. Williams, 1974. Root growth of cereal crops. Rothamsted Report for 1973, Part 2. Rothamsted Experimental Station, Harpenden, 26-65.

Werner, W., H.W. Scherer & D. Drescher, 1985. Untersuchungen über den Einfluss langjähriger Gülledüngung auf N-Fraktionen und N-Nachlieferung des Bodens. *Zeitschrift für Acker- und Pflanzenbau* 155: 137-144.

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.

Whitmore, A.P., 1996. Modelling the release and loss of nitrogen after vegetable crops. *Netherlands Journal of Agricultural Science* 44: 73-86.

Whitmore, A.P. & J.J. Schröder, 1996. Modelling the change in soil organic C and N in response to applications of slurry manure. *Plant and Soil* 184: 185-194.

Whitmore, A.P., N.J. Bradburry & P.A. Johnson, 1992. The potential contribution of ploughed grassland to nitrate leaching. *Agriculture, Ecosystems and Environment* 39: 221-233.

Wolf, J. & H. Van Keulen, 1989. Modeling long-term crop response to fertilizer and soil nitrogen. II. Comparison with field results. *Plant and Soil* 120: 23-38.

Wolf, J., C.T. De Wit & H. Van Keulen, 1989. Modeling long-term crop response to fertilizer and soil nitrogen. I. The model. *Plant and Soil* 120: 11-22.

Wyland, L.J., L.E. Jackson & K.F. Schulbach, 1995. Soil-plant nitrogen dynamics following incorporation of a mature rye cover crop in a lettuce production system. *Journal of Agricultural Science Cambridge* 124: 17-25.

SUMMARY

Maize has become a highly appreciated crop in Dutch dairy farming during the last 25 years. The current cropping technique, however, is associated with a low recovery of soil mineral nitrogen (N) and serious losses of N to the environment. This gave rise to the research described in this thesis which begins by reviewing the literature on the role of N in crop production, on N efficiency and on N losses (Chapter 1). The research reported in subsequent chapters had three objectives:

- to identify and to increase our understanding of *factors* that determine the partitioning of N inputs over crop and losses, with emphasis on maize grown on sandy soils,
- to provide *techniques* to improve the N efficiency of maize crops,
- to integrate these techniques into a consistent, comprehensive and environmentally sound N management *system*.

The results of the experiments to meet these objectives are presented in Chapters 2-6 and synthesised in Chapters 7-9.

As placement of nutrients close to the root system can improve the efficiency of nitrogen (N) use, four experiments on placement were conducted in the Wageningen Rhizolab. In these experiments the temporal and spatial distribution of maize roots was studied and N fertiliser placement options were compared (Chapter 2). The observations revealed clear vertical and lateral root length density gradients during the first 9 weeks after emergence. Root length density (Lrv), as determined in core samples 9 weeks after emergence, was found to be positively related to the number of roots counted concurrently on minirhizotron walls (n). Lrv/n ratios were 1.13, 1.76, 0.99 and 1.21 cm cm^{-1} in the successive experiments. Root numbers counted in each experiment from emergence until 9 weeks after emergence, were converted into root length density values and related to thermal time to describe Lrv as a function of the temperature sum. The average vertical root extension rates were 0.7 and 1.1 cm d^{-1} at temperatures of 13 and 16°C,

respectively. The corresponding values for the lateral extension rate were 1.0 and 1.6 cm d^{-1}.
Calculations performed at the data indicated that the N content of a 9 week old maize crop could generally not be explained by mass flow alone. Transport distances between roots and mineral N in the soil may thus have restricted the availability of N as suggested by preferential uptake of mineral N from soil compartments with a high root length density. Positioning fertiliser N close to the plant increased the recovery by a factor of 1.3 to 1.4. Dry matter (DM) yields of maize were not significantly affected by the application method of N, however. It seems that the root extension rate and the availability of N from sources other than fertiliser, were sufficient to cover the shoot demand under the prevailing circumstances.

The effect of the placement of cattle slurry on the DM yield of silage maize was studied in five experiments in which slurry was injected in spring at a rate of circa 120 kg slurry-N ha^{-1} in slots 25 cm apart ('standard injection') or in slots 75 cm apart ('banded injection'). Subsequently, maize was planted in rows 75 cm apart, parallel to the slots, either at random lateral positions in the 'standard injection' treatment or 10 cm next to the injection slots of the 'banded injection' treatment (Chapter 3). All treatments, including a control without slurry, were combined with 0 and 20-31 kg ha^{-1} subsurface banded phosphorus (P) starter fertiliser. It was found that the DM yields of silage maize were reduced by 8% on average when conventionally injected slurry ('standard injected') was not supplemented with a P starter. However, the yield reduction was limited to 2% when slurry was banded ('banded injection'). Observations on the distribution of soil mineral N (SMN) and roots in two of the experiments indicated that during the first 5-7 weeks after planting, nutrients were predominantly obtained from the soil close to the plant row. This may explain why the positive response of maize to placement was strongest and significant on P-responsive sites, indicating that placement mainly improved the availability of slurry P. Improvement of the availability of slurry N may have played a secondary role. Placement improved the recovery of slurry-N by a factor of 1.2. The results of these experiments thus suggest that slurry placement can minimise the risk of yield loss associated with reduced fertiliser inputs and contribute to a better nutrient balance between fertiliser inputs and removal in crop products.

The effects of the application time of slurry were studied in eight experiments including treatments in which circa 250 kg slurry-N ha^{-1} yr^{-1} was applied in autumn or in spring, with or without a nitrification inhibitor. The results, reported in Chapter 4, showed that adding the nitrification inhibitor dicyandiamide (DCD) to autumn-applied cattle slurry retarded nitrification and, consequently, reduced nitrate losses during winter. However, spring-applied slurry without DCD was on average associated with even lower N losses and higher maize DM yields. Nevertheless, considerable N losses were observed even with spring application of slurry. This was reflected by a large variation of the apparent N mineralisation during summer, ranging from 0.36 to 0.94 kg ha^{-1} d^{-1}. On average, 40 percent of SMN present in spring was lost during the growing season. Hence, the amounts of residual soil mineral N (RSMN) were lower than expected. Multiple regression analysis with SMN in spring, N crop uptake and cumulative rainfall as explanatory variables, could account for 79% of the variation in RSMN. Postponing slurry applications to spring and adjusting N inputs to crop requirements were insufficient to keep the nitrate concentration in groundwater below the EC threshold for drinking water.

To test the hypothesis that the recovery of SMN by crops and its subsequent utilisation for DM production may increase when the application of N is postponed until after crop emergence, nine field experiments were conducted (Chapter 5). In five experiments the effect of slurry applied at a rate of circa 340 kg N ha^{-1} before planting silage maize, was compared to the effect of a similar rate applied as a split dressings: half before planting and half at the 4-6 leaf stage. For the latter applications the slurry was either injected or banded. The remaining four experiments investigated the effect of splitting mineral fertiliser N. In these experiments, circa 150 kg slurry-N ha^{-1}, applied before planting maize, was supplemented with mineral fertiliser N at rates ranging from 40 to 160 kg ha^{-1}, either applied before crop emergence, or split. When split, 40 kg ha^{-1} of the mineral fertiliser N rate was banded at the 4-6 leaf stage.
Split applications of cattle slurry had a significant positive effect on the DM yield in two of the five experiments compared with the conventional non-split application, but only when the post-emergence slurry application was banded. Banding, however, is not in accordance with present legislation. Split applications of mineral fertiliser N had a significant positive effect in one experiment where rainfall was excessive but not in the others. The

results provide insufficient evidence to justify recommending farmers to split applications. SMN sampling at the 4-6 leaf stage should hence be considered a check of the appropriateness of early N applications followed by exceptional weather conditions rather than a routine observation on which the post-emergence N dressing is to be based in a deliberate splitting strategy. The data suggest that the financial return from a 40 kg ha^{-1} supplementation with mineral fertiliser N, is questionable if there is more than 175 kg N ha^{-1} in the upper 0.6 m soil layer at the 4-6 leaf stage.

The presence of RSMN after the harvest of maize seems inevitable to a certain extent. Rye and grass cover crops can potentially intercept RSMN, reduce overwinter leaching, transfer SMN to next growing seasons and reduce the fertiliser need of subsequent crops. These aspects were studied for 6 years in continuous silage maize production systems with N input levels ranging from 20 to 304 kg total N ha^{-1}, applied as mineral fertiliser and/or slurry (Chapter 6). It was found that rye and grass cover crops were able to absorb on average 40 kg N ha^{-1} in the aboveground plant parts. The actual N uptake was largely determined by winter temperatures and hardly by residual SMN. At low N input levels, cover crops reduced N leaching in accordance with their N uptake. At high N input levels, however, the reduction of leaching losses exceeded the sequestering capacity of the cover crop, suggesting that cover cropping stimulated the immobilisation of N or the loss of N via denitrification.
Cover crops had no positive effect on maize yields at larger N rates and under these conditions cover crops did not improve the conversion of SMN into crop N. This was only partly reflected by an increase in residual SMN on plots where cover crops had been incorporated, as much of the excess N on maize had already been lost during the growing season. In N deficient maize production systems, however, cover crops increased the DM yield of maize. Their effect was equivalent to the effect of fertiliser N rates amounting to 105% and 44% of the aboveground N in rye and grass, respectively. In the first few years, cover crops decomposed incompletely during the growing season following their incorporation. Over the years, however, their effects on subsequent maize crops increased. This supports the hypothesis that the effects of cover crops can accumulate when grown year after year. Averaged over the 6 years, 115% and 73% of the aboveground rye N and grass N, respectively, were recovered in the crop-soil system.

The residual effect of manuring has to be quantified if the financial returns of farming systems are to be maximised and contamination of the environment is to be avoided. It is especially important to quantify the residual effect on maize land in The Netherlands, since manure has been dumped on this land for over 25 years. A simulation model was therefore calibrated with data from a long-term field experiment and used to estimate the effects of Dutch manuring practice on maize land. The time course of the N mineralisation rate was estimated for three scenarios: i) following actual manure applications, which have declined with time (A scenario); ii) assuming continuous applications in accordance with the present and anticipated legislation (P scenario); iii) assuming applications of 200 kg mineral fertiliser N ha^{-1} yr^{-1} only (M scenario). The results of this scenario study are presented in Chapter 7. They show that the estimated mineralisation rate (following the A scenario) for 1995 is 23-31 kg N ha^{-1} yr^{-1} higher than when manure is applied at moderate rates (following the P scenario). The corresponding estimates for the year 2005 still amount to 18-19 kg N ha^{-1} yr^{-1}.
These calculations suggest that it may be extremely difficult to maintain soil organic N pools with mineral fertiliser only. Consequently, the mineralisation rate following the M scenario decreases with time, as do the yields of silage maize. The magnitude of the residual effect found in the present study, indicates that recommendations need to be fine-tuned and that there is scope to do so. The distinct long-term impact of previous manure applications also underlines the need to interpret results from short-term experiments with caution.

The current use of N in silage maize production in The Netherlands leads to considerable N losses to the environment. However, maize growers fear that reducing N inputs so as to minimise N losses, might depress yields. The study described in Chapter 8 was conducted to investigate this. It aimed to quantify: 1) the response of silage maize DM yields to N, 2) the economically optimal N reserve, and 3) the trade-off between silage maize DM yield and N losses. The indicators of N losses used in this study were the difference between N input and N uptake and the post-harvest residual soil mineral N. In the study, regression models were used to fit DM yields and N uptakes of silage maize measured in 25 experiments on sandy soils in The Netherlands to the sum (SUMN) of the soil mineral N reserve (SMN_{early}) in March-April, plus mineral N in fertiliser, plus ammonium N in spring-applied slurry. The values obtained for the economically optimal SUMN in the upper 30 and 60 cm of soil were respectively 173 and 195 kg N ha^{-1} (both with standard errors of 15 kg N ha^{-1}). The economically optimal SUMN was not significantly related to the attainable DM yield.

The DM yield and N uptake were also fitted to the measured soil mineral N reserve (SMN_{late}) in May-June which was determined in 10 of the experiments. The values obtained for the economically optimal SMN_{late} amounted to 147 and 229 kg N ha^{-1} (standard errors of 14 and 15 kg N ha^{-1}, respectively) for sampling depths of 30 and 60 cm, respectively.

The apparent N recovery (ANR) of maize averaged 53% at the economically optimal SUMN. The ANR rose considerably, however, when N was applied at lower rates, indicating that N losses may be much smaller in less intensive maize cropping. When maize was fertilised at 100 kg N ha ha^{-1} below the economic optimum, the ANR was 73%, the difference between the mineral N input and the N crop uptake decreased by 57 kg N ha ha^{-1} and the soil mineral N residue at the end of the growing season (0-60 cm) decreased by 24 kg N ha ha^{-1}. The associated reduction in DM yield averaged 16%.

The general conclusion from this study is that adjusting the N input to a level below the economically optimal rate can reduce the risks for N losses to the environment associated with conventional maize production, with a limited effect on silage yields.

In Chapter 9 the results from previous chapters are drawn together and generalised. It was shown that N losses in the production of maize appear to originate from a combination of soil, climate and crop characteristics. In The Netherlands, maize is mainly grown on sandy soils. These soils have a limited capacity to retain water and therefore N may easily be lost to greater depths when it is available or applied too early. Nitrogen deeper in the soil can be intercepted in time less easily by the maize root system. It is possible to minimise the risks for an insufficient synlocalisation of N and roots by postponing N applications. However, the N from postponed applications may also be recovered poorly, as the application may coincide with quantities of N becoming available from mineralisation, making the application redundant. Moreover, if applied after crop emergence, the late-applied N may be positioned inappropriately in relation to the positioning of functioning roots. All in all, the rationale of applying mineral N (including that from manure) is to supply N when and where the maize needs N for its biomass production, at a time that the maize root system is still unable to obtain that N sufficiently from soil reserves. These aspects limit the time span during which the application of mineral N is effective. N losses resulting from the current technique for cropping maize on Dutch sandy soils can thus be attributed to a combination of *factors*:

- too high application rates of N due to regional slurry surpluses and a tendency for maize growers to compensate *a priori* for unforeseen N losses,
- inaccessibility of the soil N reserves for roots in a cold and wet spring,
- too early or too late applications of N,
- application of N in non-rooted or poorly rooted soil compartments,
- N mineralisation outside the period that maize takes up N.

From the research described in this thesis it is concluded that maize growers can reduce N losses by using the following cropping *techniques*. These techniques will only become effective, however, if they are used concomitantly in a consistent and comprehensive *system*:

- drastically reducing the N application rate (including manure N),
- fine-tuning the application rate of N by taking account of site characteristics such as the intrinsic soil mineral N reserves, the manuring history and the N contribution from previous crops including cover crops,
- confining the application of N to those parts of the soil profile where a high root length density is anticipated,
- postponing the application of N until shortly before sowing,
- restricting post-emergence applications of N to situations where N deficiency is indicated by the soil mineral N reserves,
- growing cover crops after maize.

These cropping techniques are currently insufficiently exploited in conventional maize cropping sytems. Consequently, conventional cropping systems of maize will not yield a quality of the shallow groundwater under maize land that meets the EC Nitrate Directive for drinking water.
Although it appears to be technically feasible to introduce 'nitrate-safe' cropping systems for maize, consisting of a combination of measures including reduced manure and fertiliser inputs, placement of manure and of fertilisers and growing cover crops during winter, this will inevitably cost

money. The way the current conventional cropping technique is laid out and implemented makes it difficult but not impossible to introduce these alternative systems. Without the suggested combination of additional measures, the anticipated Dutch legislation on the use of manure and fertilisers will probably insufficiently improve the quality of the groundwater under maize land in many regions with sandy soils.

Keywords:

Apparent recovery, cover crop, fertiliser placement, fertiliser splitting, leaching, manure, mineralisation, minirhizotron, nitrate leaching, nitrification inhibitor, nitrogen recovery, phosphorus, placement, recovery, residual effect, residual nitrogen, response model, root distribution, root length density, silage maize, simulation, slurry, soil sampling, *Zea mays* L.

SAMENVATTING

Maïs is de afgelopen 25 jaar uitgegroeid tot een hooggewaardeerd gewas in de Nederlandse melkveehouderij. De gangbare teeltwijze van maïs kenmerkt zich evenwel door een geringe benutting van stikstof (N) vanuit de bodem en grote verliezen van N naar de omgeving. Dit gegeven vormde aanleiding voor het in dit proefschrift beschreven onderzoek. In Hoofdstuk 1 wordt een overzicht gegeven van de literatuur over de rol van N bij de gewasproductie, over de benutting van N en over de verliezen van N. Het onderzoek beschreven in het vervolg van dit proefschrift had tot doel om:

- *factoren* aan te wijzen en te doorgronden die bepalen of N door het gewas wordt opgenomen of verloren gaat, met name voor maïs geteeld op zandgrond,
- *instrumenten* aan te dragen om de N benutting door maïs te verbeteren,
- deze instrumenten te combineren tot een samenhangend, milieukundig verantwoord *systeem* van N beheer.

Ter verwezenlijking van dit doel werden veldproeven uitgevoerd waarvan de resultaten worden gepresenteerd in de Hoofdstukken 2 tot en met 6. De synthese van deze resultaten wordt behandeld in de Hoofdstukken 7 tot en met 9.

In het eerste hoofdstuk van het proefschrift wordt duidelijk gemaakt dat de uitbating van N bepaald wordt door de hoeveelheid toegediende voedingsstoffen, het moment van toediening en de wijze van toediening. De betekenis van deze factoren voor maïsteelt op zandgrond in Nederland werd gekwantificeerd en beoordeeld in veldproeven waarvan de resultaten worden gepresenteerd in de volgende hoofdstukken.

Plaatsing van N- of fosfor-(P-) meststoffen nabij het wortelstelsel kan de benutting van meststoffen verbeteren en de gift benodigd voor maximale productie verkleinen. Dit leidt tot een betere balans tussen de voedingsstoffen die met meststoffen worden aangevoerd en met het gewas worden afgevoerd. Vanuit dat oogpunt werden twee series proeven uitgevoerd.

In vier proeven uitgevoerd in het Wageningen Rhizolab (Hoofdstuk 2), werd onderzocht hoe maïswortels in de loop van de tijd door de bodem verdeeld zijn. Daarbij zijn verschillende toedieningsplaatsen van kunstmest-N vergeleken. De waarnemingen gaven aan dat de wortellengtedichtheden gedurende de eerste 9 weken na opkomst zeer sterke verticale en horizontale gradiënten vertoonden.
De wortellengtedichtheid zoals bepaald in boormonsters, 9 weken na opkomst hing positief samen met de aantallen wortels die tezelfdertijd op minirhizotronwanden geteld werden. De aantallen wortels die op voorgaande data in elke afzonderlijke proef geteld werden, werden omgezet naar wortellengtedichtheden en in verband gebracht met temperatuursommen. De beschrijving van dit verband gaf aan dat de gemiddelde verticale uitbreidingssnelheid van wortels 0,7 en 1,1 cm per dag bedraagt bij temperaturen van, respectievelijk, 13 en 16°C. De overeenkomstige zijdelingse uitbreidingssnelheid bedroeg, respectievelijk, 1,0 en 1,6 cm per dag. Berekeningen gaven aan dat de N opname van 9 weken oude maïs in het algemeen niet door massastroming alleen verklaard kon worden. Als gevolg daarvan kunnen de transportafstanden tussen wortels en minerale bodem-N de beschikbaarheid van N beperkt hebben, zoals gesuggereerd door de voorkeursopname van N vanuit bodemcompartimenten met een hoge wortellengtedichtheid. De uitbating van N werd met een factor 1,3 tot 1,4 verhoogd door plaatsing nabij de maïsrij. Een positief effect op de drogestof (DS) opbrengst van maïs bleef echter uit. Kennelijk waren de uitbreidingssnelheid van wortels en de beschikbaarheid van N vanuit andere bronnen dan kunstmest onder de gegeven omstandigheden voldoende om aan de vraag naar N door het gewas te voldoen.

Het effect van drijfmestplaatsing op de DS-opbrengst van maïs werd bestudeerd in vijf proeven (Hoofdstuk 3). In deze proeven werd een gift van circa 120 kg drijfmest-N per ha in het voorjaar geïnjecteerd in sleuven die of 25 cm uiteen lagen (standaard-injectie), of 75 cm uiteen lagen (rijeninjectie). Vervolgens werd maïs gezaaid op een rijenafstand van 75 cm parallel aan de sleuven op een willekeurige positie (standaard-injectie) of 10 cm naast de sleuf (rijeninjectie). Alle behandelingen, inclusief een onbemest object, werden gecombineerd met een rijenbemesting van 0 en van 20-31 kg kunstmest-P per ha.
De DS-opbrengsten van snijmaïs bleven circa 8% achter als de standaard-injectie van mest niet gecombineerd werd met een kunstmest-P

rijenbemesting. Echter, de opbrengstderving bleef beperkt tot 2% als de mest als rijeninjectie werd toegepast.
Waarnemingen van de verdeling van minerale bodem-N en wortels in twee van de proeven gaven aan dat nutriënten gedurende de eerste 5-7 weken na zaai hoofdzakelijk werden geleverd vanuit het bodemvolume nabij de plantrij. Dit kan verklaren waarom snijmaïs positief reageerde op een rijeninjectie van dierlijke mest. Deze reactie was het sterkst op percelen die ook sterk positief op kunstmest-P reageerden, waaruit de conclusie kan worden getrokken dat mestplaatsing vooral de beschikbaarheid van drijfmest-P verbeterd heeft. Verbetering van de beschikbaaarheid van drijfmest-N heeft een nevenrol gespeeld. Plaatsing verbeterde de uitbating van mest-N met een factor 1,2.
De resultaten geven aan dat mestplaatsing het risico van opbrengstverlies als gevolg van een verminderde meststof-inzet kan verkleinen. Dit kan leiden tot een betere balans tussen de voedingsstoffen die met meststoffen worden aangevoerd en met gewassen worden afgevoerd.

De effecten van het toedieningstijdstip van drijfmest werden bestudeerd in acht proeven waarin drijfmestgiften van circa 250 kg N per ha per jaar in de herfst of in het voorjaar werden gegeven, met en zonder nitrificatieremmer. De resultaten, weergegeven in Hoofdstuk 4, geven aan dat de toevoeging van de nitrificatieremmer dicyaandiamide (DCD) aan mest die in de herfst werd toegediend, de nitrificatie vertraagde. Dit beperkte het verlies van nitraat gedurende de winter. Echter, voorjaarstoediening zonder toevoeging van de nitrificatieremmer DCD ging gemiddeld met geringere N verliezen en hogere DS-opbrengsten van snijmaïs gepaard. Ook bij voorjaarstoediening van mest traden nog aanzienlijke verliezen van N op. Gemiddeld ging 40% van de minerale bodem-N die in het voorjaar aanwezig was, gedurende het groeiseizoen verloren. Als gevolg daarvan was de hoeveelheid residuele minerale bodem-N aan het einde van het groeiseizoen kleiner dan verwacht. Meervoudige regressieanalyse met als verklarende variabelen de voorraad minerale bodem-N in het voorjaar, de N opname door het gewas en de gesommeerde neerslag, verklaarde 79% van de waargenomen variatie in de voorraad residuele minerale bodem-N. Uitstel van de drijfmesttoediening van de herfst naar het voorjaar en afstemming van de N gift op de vraag naar N door het gewas, bleken onvoldoende om het nitraatgehalte van het grondwater onder de EU-richtlijn voor drinkwater te houden.

De uitbating van N door gewassen en de omzetting hiervan in DS kan verbeteren door de toediening van N gedeeltelijk uit te stellen tot na opkomst van het gewas. De betekenis van deze strategie voor snijmaïs werd bestudeerd in negen veldproeven (Hoofdstuk 5). In vijf proeven werd het effect van een mestgift van circa 360 kg N per ha, toegediend voor het zaaien, vergeleken met het effect van eenzelfde gift waarvan de ene helft voor het zaaien en de andere helft in het 4-6 blad-stadium werd toegediend. In laatstgenoemd stadium werd de drijfmest geïnjecteerd of oppervlakkig, bandsgewijs toegediend.
In vier andere proeven werd het effect van de deling van kunstmest-N giften bestudeerd. In die proeven werd een gift van circa 150 kg N per ha drijfmest, toegediend voor het zaaien van de maïs, aangevuld met kunstmest-N in hoeveelheden variërend van 40 to 160 kg N per ha. Deze kunstmest werd ofwel geheel voor opkomst van het gewas gegeven of gedeeld. In dat laatste geval werd 40 kg N per ha bandsgewijs tussen de rijen gegeven in het 4-6 blad-stadium.
Deling van de drijfmestgift verhoogde de DS-opbrengst van snijmaïs significant in twee van de vijf veldproeven vergeleken met de gebruikelijke ongedeelde toediening, maar alleen als de na-opkomst-toediening oppervlakkig was toegediend. Deze toedieningswijze is echter niet langer in overeenstemming met de huidige wetgeving. Deling van de kunstmestgift verhoogde de DS-opbrengst significant in een veldproef waarin uitzonderlijk veel regen viel maar niet in de andere proeven. De resultaten geven onvoldoende aanleiding om snijmaïstelers aan te raden om mest- of kunstmestgiften te delen. Bemonstering van de bodem op N in het 4-6 blad-stadium moet dan ook meer gezien worden als een controle op de juistheid van de N voorziening na een vroege toediening van mest gevolgd door uitzonderlijke weersomstandigheden dan als een waarneming waarop na-opkomst-giften dienen te worden gebaseerd als onderdeel van een bewuste delingsstrategie. De resultaten geven aan dat de profijtelijkheid van een na-opkomstgift van 40 kg N per ha twijfelachtig is als in het 4-6 blad-stadium meer dan 175 kg minerale N per ha in de bovenste 60 cm van de bodem wordt aangetroffen.

De aanwezigheid van residuele minerale bodem-N na de oogst van maïs is tot op zekere hoogte onvermijdelijk. De wintergewassen rogge en gras kunnen deze N in beginsel onderscheppen, op die manier de uitspoeling van N gedurende de winter beperken, de behouden N naar het volgende

voorjaar overdragen en als gevolg daarvan de mestbehoefte van een volgteelt verkleinen. Deze aspecten werden gedurende zes jaar bestudeerd in een continuteelt van snijmaïs bij een jaarlijkse toediening van 20 tot 304 kg totaal N per ha in de vorm van kunstmest en/of drijfmest (Hoofdstuk 6). Rogge en gras waren in staat gemiddeld 40 kg N per ha in de bovengrondse delen op te nemen. De gerealiseerde N opname werd grotendeels bepaald door de temperatuur gedurende het winterhalfjaar en nauwelijks door de hoeveelheid residuele minerale bodem-N. Bij lage niveaus van N toediening verlaagden wintergewassen de uitspoeling overeenkomstig hun N vastlegging. Bij hoge niveaus van N toediening was de verlaging van de uitspoeling groter dan verklaard kon worden uit de N vastlegging in de wintergewassen. Dit suggereert dat wintergewassen het verlies van N via denitrificatie of de immobilisatie van N kunnen hebben vergroot.
Wintergewassen hadden geen positief effect op de opbrengst van snijmaïs bij een hoog niveau van N toediening en onder dergelijke omstandigheden verbeterden wintergewassen de omzetting van bodem-N in gewas-N niet. Dit kwam slechts ten dele tot uiting in een toename van de hoeveelheid residuele minerale bodem-N op veldjes waar een wintergewas was ingewerkt omdat een teveel aan N voor een groot deel al gedurende de zomer verloren bleek te gaan. In een N behoeftige situatie, echter, verhoogden wintergewassen de DS-opbrengst van snijmaïs wel. Het effect was gelijk aan dat van een kunstmestgift ter grootte van 105% en 44% van de bovengrondse N opbrengst van, respectievelijk, rogge en gras.
In de eerste jaren van de proef bleken ingewerkte wintergewassen onvolledig te verteren. In de loop van de jaren, echter, werden de effecten op volgteelten groter. Dit ondersteunt de veronderstelling dat de effecten van wintergewassen bij herhaald gebruik een cumulatief karakter kunnen hebben. Gemiddeld over de zes proefjaren werd 115% en 73% van de bovengrondse N opbrengst van wintergewassen gedurende het zomerhalfjaar weer teruggevonden in gewas en bodem.

Kwantificering van de nawerking van organische meststoffen is nodig voor een zo hoog mogelijk rendement van teeltsystemen en om milieu-verontreiniging tegen te gaan. Dit is speciaal van toepassing op maïsland in Nederland omdat dat gebruikt is voor het dumpen van mest gedurende meer dan 25 jaar. Een simulatiemodel werd geijkt met gegevens van een veeljarige proef en vervolgens gebruikt om een schatting te maken van de effecten van deze bemestingspraktijk. Het verloop van de N mineralisatie in

de tijd werd geschat voor drie scenario's: bij het geschatte feitelijke gebruik van mest dat afnam met de jaren (A scenario), bij een verondersteld constant gebruik van mest in overeenstemming met de geldende en voorziene wetgeving (P scenario) en bij een verondersteld jaarlijks constant gebruik van 200 kg kunstmest-N per ha (M scenario). De resultaten van deze scenario studie worden behandeld in Hoofdstuk 7.
De feitelijke N mineralisatie (volgens het A scenario) is in 1995 23-31 kg N per ha per jaar groter geschat dan wanneer mest vanaf het begin volgens de huidige wetgeving zou zijn toegediend (volgens het P scenario). Het overeenkomstige effect voor 2005 is op 18-19 kg N per ha per jaar geschat.
De berekeningen gaven voorts aan dat het lastig kan zijn om N voorraden in de bodem op peil te houden met alleen kunstmest-N. Als gevolg daarvan nam de geschatte mineralisatie bij het M scenario met de jaren af, evenals de opbrengst van snijmaïs. De grootte-orde van de gevonden nawerking maakt duidelijk dat fijnregeling van bemestingsadviezen kan en moet plaatsvinden. De omvang van de nawerking van eerder gegeven mest maakt ook duidelijk dat de resultaten van kortlopende proeven met de nodige voorzichtigheid dienen te worden geïnterpreteerd.

Het gebruik van N is onmisbaar voor een profijtelijke teelt van snijmaïs. Ook als N wordt toegepast in geringere hoeveelheden dan economisch gewenst, kan het gebruik van N een negatief effect op het milieu hebben. Het onderzoek gepresenteerd in Hoofdstuk 8 had tot doel het opbrengst-verlies te bepalen als omwille van milieu-eisen minder N gegeven moet worden dan economisch te rechtvaardigen valt.
Daartoe zijn de DS-opbrengst en N opname van snijmaïs zoals waargenomen in 25 veldproeven, met behulp van diverse regressie-modellen in verband gebracht met de som (NSOM) van de hoeveelheid minerale bodem-N ($Nmin_{vroeg}$) in de bovenste 60 cm in het vroege voorjaar, toegediende kunstmest-N en toegediende ammoniakale N in dierlijke mest. De economisch optimale NSOM bedroeg gemiddeld 195 kg N per ha en hing nauwelijks af van het opbrengstniveau.
De DS-opbrengst en de N opname werden ook in verband gebracht met de gemeten hoeveelheid minerale bodem-N ($Nmin_{laat}$) in de bovenste 60 cm in het late voorjaar zoals bepaald in 10 van de proeven. De economisch optimale $Nmin_{laat}$ bedroeg gemiddeld 229 kg N per ha.
De uitbating van N door snijmaïs bedroeg 53% bij de economisch optimale NSOM. De uitbating steeg aanmerkelijk als minder N werd gegeven dan

gerechtvaardigd was op louter economische gronden. Daaruit bleek dat de uitstoot van N veel geringer kan zijn in een minder intensief teeltsysteem. Als 100 kg N per ha minder werd toegediend dan economisch gerechtvaardigd was, steeg de uitbating naar 73%, daalde het N overschot met 57 kg N per ha en nam de hoeveelheid residuele minerale bodem-N af met 24 kg N per ha. De opbrengstderving waarmee deze maatregel gepaard ging bedroeg gemiddeld 16%.

In Hoofdstuk 9 worden de resultaten uit eerdere hoofdstukken geïntegreerd en gegeneraliseerd. De voorgaande hoofdstukken toonden aan dat N verliezen bij de teelt van maïs hun oorsprong vinden in een combinatie van bodem-, klimaat- en gewaskenmerken. In Nederland wordt maïs hoofdzakelijk op zandgrond geteeld. Dit soort gronden heeft een gering vermogen om vocht vast te houden en N kan dientengevolge gemakkelijk naar grotere diepten verloren gaan als het te vroeg beschikbaar komt of te vroeg wordt toegediend. Stikstof op grotere diepte kan minder gemakkelijk op tijd onderschept worden door maïswortels. Risico's van een onvoldoende synlocalisatie van wortels en N kunnen worden beperkt door de toediening uit te stellen. De N van uitgestelde giften, echter, kan ook slecht benut worden omdat de toediening kan samenvallen met het vrijkomen van N door mineralisatie. Dat maakt de N van uitgestelde giften overbodig. Bovendien kan N die pas na opkomst wordt toegediend een verkeerde positie hebben ten opzichte van actieve wortels. Stikstoftoediening moet daarom gericht zijn op het aanbieden van N op momenten en plaatsen dat het wortelstelsel van maïs nog niet voldoende in staat is om aan de vraag te voldoen vanuit de bodemreserves. Dit gegeven beperkt de tijdspanne gedurende welke de toediening van N effectief is. De aanmerkelijke N verliezen waarmee de gangbare teelt van maïs op Nederlandse zandgronden gepaard gaat, kunnen vanuit die optiek worden toegeschreven aan een combinatie van *factoren*:

- een te hoog aanbod van N als gevolg van mestoverschotten enerzijds en de geneigdheid van telers om onverhoopte N tekorten op voorhand te compenseren anderzijds,
- de onbereikbaarheid van N voor wortels onder natte en koude weersomstandigheden,
- een te vroege of te late toediening van N,

- het toedienen van N in slecht of niet-doorwortelde delen van het bodemprofiel,
- het vrijkomen van minerale bodem-N buiten de periode dat maïs tot N opname in staat is.

Telers van maïs kunnen N verliezen beperken door van de volgende *instrumenten* gebruik te maken. Deze instrumenten zijn alleen dan effectief als zij gelijktijdig worden gebruikt in een samenhangend *systeem*:

- een drastische verlaging van het N aanbod, waaronder dat van mest-N,
- een verfijning van het N aanbod op basis van perceelskarakteristieken als de bodemvoorraad, het bemestingsverleden en de bemestende waarde van voorvruchten waaronder wintergewassen,
- de toediening van N in alleen dat deel van het profiel waar een hoge dichtheid van maïswortels verwacht mag worden,
- de toediening van N tot kort voor het zaaien uit te stellen en alleen dan tot aanvullende N giften na opkomst over te gaan als de bodemvoorraad dat aangeeft,
- de teelt van wintergewassen na de oogst van maïs.

Geconcludeerd wordt dat gangbare teeltsystemen voor snijmaïs bij een economisch optimale N gift niet kunnen leiden tot een grondwaterkwaliteit die voldoet aan de EU Nitraat Richtlijn voor drinkwater.
Introductie van 'nitraat-veilige' teeltsystemen lijkt technisch goed mogelijk maar gaat wel met kosten gepaard. Maatregelen ten behoeve van zo'n *teeltsysteem* bestaan uit een gecombineerde toepassing van gereduceerde mest- en kunstmestgiften, plaatsing van mest en van kunstmest en de teelt van wintergewassen. De inrichting en uitvoering van de huidige teeltwijze maken de introductie van deze maatregelen lastig maar technisch niet onmogelijk. Zonder de genoemde combinatie van maatregelen zal de voorziene mestwetgeving (MINAS) op droge zandgronden waarschijnlijk niet tot acceptabele nitraatgehalten van het bovenste grondwater onder snijmaïsland leiden.

Trefwoorden:

Bemestingswaarde, beworteling, dierlijke mest, drijfmest, fosfaat, grondmonster, maïs, mineralisatie, minirhizotron, nawerking, nitraatuitspoeling, nitrificatieremmer, plaatsing, residuele stikstof, responsmodel, rijenbemesting, simulatie, snijmaïs, stikstofdeling, stikstofuitbating, uitspoeling, wintergewas, wortellengtedichtheid, *Zea mays* L.

Appendix 1.

Formularium for the relationships between nitrate concentration in groundwater, residual soil mineral N supply after the harvest of maize, the amount of N available for crop uptake, the dry matter yield of maize, the financial returns and the N- and P-surplus.

Parameters (in brackets [...] the values chosen in the present study are given):

SMN — soil mineral N supply in spring under fallow, *kg ha⁻¹* [40]

RSMNCC — reduction of SMN in the presence of a cover crop, *kg kg⁻¹* [10]

NH4NF — relative share of ammoniacal N in total N in slurry, *kg kg⁻¹* [0.5 for cattle slurry]

NPRAT — N concentration in slurry relative to P_2O_5 concentration, *kg kg⁻¹* [2.72 for cattle slurry]

NDEP — atmospheric N deposition, *kg ha⁻¹* [40]

MDELS — deviation from the usual apparent mineralization during summer, *kg ha⁻¹* [0 and -30 for environments with a high and low N supplying capacity]

FMDELS — fraction of MDELS available for plant uptake, *kg kg⁻¹* [0.6]

MDELW — deviation from the usual apparent mineralization during winter, *kg ha⁻¹* [0 and -10 for environments with a high and low N supplying capacity]

FBDF — efficiency of subsurface band dressed fertiliser relative to that of broadcast fertiliser, *kg kg⁻¹* [1.25]

FBDM — efficiency of band-injected manure relative to that of conventionally injected manure, *kg kg⁻¹* [1.25]

FDEN	fraction of the nitrate that is denitrified in deeper layers, *kg* kg^{-1} [0 for dry sandy soils]
NUPCC	aboveground N uptake in cover crop, *kg* ha^{-1} [30]
RFVCC	relative fertiliser value of a cover crop expressed as the fraction of NUPCC becoming available to subsequent crop, *kg* kg^{-1} [0.75]
FCCS	fraction of NUPCC decomposing within growing season, *kg* kg^{-1} [0.95]
PFER	P from fertiliser, *kg* P_2O_5 ha^{-1} [0]
P%MA	P concentration in maize DM, *kg* P_2O_5 *(100* kg^{-1}*)* [0.5]
PRIMA	price of maize, *NLG* kg^{-1} [0.25]
PRICC	price of cover crop, *NLG* ha^{-1} [0]
PRIFER	price of fertiliser N, *NLG* kg^{-1} [1.25]
PRIBD	price of band dressing, *NLG* ha^{-1} [0]
LFPS	levy-free P-surplus, *kg* P_2O_5 ha^{-1} [20]
ULCPS	upper level for the moderately charged P-surplus, *kg* P_2O_5 ha^{-1} [25]
LPMS	levy on the P-surplus in the moderately charged range, *NLG* P_2O_5 kg^{-1} [5]
LPSS	levy on the P-surplus in the severly charged range, *NLG* P_2O_5 kg^{-1} [20]
LFNS	levy-free N-surplus, *kg N* ha^{-1} [100]
LNS	levy on the N-surplus in the charged range, *NLG N* kg^{-1} [1.50]

Input variables:

NH4N	ammoniacal N from slurry, *kg* ha^{-1}
NFER	mineral N from fertiliser, *kg* ha^{-1}

Output variables:

SUMNP	summed mineral N inputs apparently available to the crop, *kg* ha^{-1}
NUPMA	aboveground N uptake in maize, *kg* ha^{-1}
DMYMA	aboveground DM yield of maize, *kg* ha^{-1}
SUMNR	summed mineral N inputs contributing to build-up of RSMN, *kg* ha^{-1}
RSMN	residual soil mineral N, *kg* ha^{-1}
SUMNW	summed mineral N sources exposed to overwinter leaching, *kg* ha^{-1}
NO3C	nitrate concentration during winter, *mg* l^{-1}
ORGN	total N from slurry, *kg* ha^{-1}
NSMINAS	N surplus according to MINAS definition, *kg* ha^{-1}
NSTOTAL	N surplus including atmospheric deposition, *kg* ha^{-1}
ORGP	P from slurry, *kg* P_2O_5 ha^{-1}
PUPMA	aboveground P uptake in maize, *kg* P_2O_5 ha^{-1}
PSMINAS	P surplus according to MINAS definition, *kg* P_2O_5 ha^{-1}
PRIORG	price of manure N, *NLG* kg^{-1}
FRET	financial returns of the cropping system, *NLG* ha^{-1}

Formulas:

$$SUMNP = \min((SMN + \mathrm{if}(\text{cover crop} = \text{yes}, RSMNCC, 0) + \mathrm{if}(\text{band application} = \text{yes}, FBDF, 1) * NFER + \mathrm{if}(\text{band application} = \text{yes}, FBDM, 1) * NH4N + MDELS * FMDELS + \mathrm{if}(\text{cover crop} = \text{yes}, NUPCC * RFVCC, 0)), 287)$$

$$NUPMA = 61.26 + 1.1038 * SUMNP - 0.001920 * SUMNP^2$$

(derived from Chapter 8)

$$DMYMA = -4.82 + 0.1749 * NUPMA - 0.0003812 * NUPMA^2$$

(derived from Chapter 8)

$$SUMNR = SMN + \mathrm{if}(\text{cover crop} = \text{yes}, RSMNCC, 0) + \mathrm{if}(\text{band application} = \text{yes}, 2 - FBDF, 1) * NFER + \mathrm{if}(\text{band application} = \text{yes}, 2 - FBDM, 1) * NH4N + MDELS + \mathrm{if}(\text{cover crop} = \text{yes}, NUPCC * FCCS, 0)$$

$$RSMN = 33.9 + 0.0008459 * SUMNR^2$$

(derived from Chapter 8)

$$SUMNW = RSMN - \mathrm{if}(\text{cover crop} = \text{yes}, NUPCC, 0) + \mathrm{if}(\text{cover crop} = \text{yes}, (NUPCC * (1-FCCS)), 0) + MDELW$$

$$NO3C = \max((1-FDEN) * (-71.5 + 4.175 * SUMNW - 0.00973 * SUMNW^2), 0))$$

(derived from Figure 9.6 in General Discussion)

$$ORGN = NH4N / NH4NF$$

$$NSMINAS = NFER + ORGN - NUPMA$$

$$NSTOTAL = NSMINAS + NDEP$$

ORGP	=	NH4N / NH4NF / NPRAT
PUPMA	=	DMYMA * 10 * P%MA
PSMINAS	=	PFER + ORGP - PUPMA
PRIORG	=	PRIFER * NH4NF

FRET	=	(PRIMA * DMYMA)
		(if (cover crop = yes, PRICC, 0) +
		PRIFER * NFER + PRIORG * ORGN +
		if (band application = yes, PRIBD, 0) +
		if (PSMINAS<LFPS,0,(if (PSMINAS<ULCPS, (PSMINAS-
		LFPS) * LPMS, (ULCPS-LFPS) * LPMS +
		(PSMINAS-ULCPS) * LPSS))) +
		if (NSMINAS<LFNS,0,(NSMINAS-LFNS) * LNS))

CURRICULUM VITAE

Jaap Jan Schröder werd op 31 mei 1957 geboren in Castricum. In 1976 behaalde hij het Gymnasium ß-diploma aan het Murmellius Gymnasium te Alkmaar. Vanaf 1976 studeerde hij aan de Landbouwhogeschool (LH) in Wageningen, richting Landbouwplantenteelt. In 1983 studeerde hij af met als doctoraalvakken landbouwplantenteelt, entomologie en onkruidkunde. Eind 1983 werd hij aangesteld als onderzoeker Voedergewassen bij het Proefstation voor de Akkerbouw en de Groenteteelt in de Vollegrond (PAGV) in Lelystad. In de daarop volgende acht jaar verrichtte hij onderzoek naar onder meer de effecten van plantdichtheid, vruchtwisseling en bemesting bij snijmaïs. In 1991 stapte hij over naar het Centrum voor Agrobiologisch Onderzoek (CABO) in Wageningen om bij de afdeling Agrosysteemkunde onderzoek te doen naar de benutting van stikstof in ruwvoederproductiesystemen en naar de ontwikkeling van geïntegreerde akkerbouwproductiesystemen. Sinds 1995 werkt hij in vervolg op de fusie tussen het CABO en het Instituut voor Bodemvruchtbaarheid (IB), bij de afdeling Bodem- en Nutriëntenbeheer van het DLO-Instituut voor Agrobiologisch en Bodemvruchtbaarheidsonderzoek (AB-DLO). Daar houdt hij zich bezig met de ontwikkeling van milieuvriendelijke bemestings-strategieën. In het kader van die functie is hij coördinator van het onderzoek op het Ecologisch Proefbedrijf H.J. Lovinkhoeve in Marknesse.