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Relation between soil mineral nitrogen before sowing and optimum nitrogen fertilization in onions

C.L.M. DE VISSER[1], W. VAN DEN BERG[1] AND H. NIERS[2]

[1] Research Station for Arable Farming and Field Production of Vegetables (PAGV), P.O. Box 430, NL-8200 AK Lelystad, the Netherlands
[2] DLO-Research Institute for Agriobiology and Soil Fertility (AB-DLO), P.O. Box 129, NL-9750 AC, Haren, the Netherlands

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Abstract

To study the relationship between the amount of soil mineral nitrogen before sowing of onions (N_{min}) and the optimum amount of nitrogen fertilizer (N_{opt}), 36 multi-level fertilizer nitrogen trials were conducted between 1978 and 1982. For 26 trials N_{opt} was within the studied range (0–200 kg N ha^{-1}) and could be estimated using a quadratic response function. A significant linear relationship between N_{opt} and N_{min} before sowing was only found when N_{min} in the layer 0-30 cm was considered. The same 26 trials were analysed together using a quadratic and a linear exponential response function. However, with both methods the yield predicted from N_{min} did not prove to be superior to a fixed nitrogen application rate of about 125 kg of nitrogen ha^{-1}. A verification pointed out that the relationship overestimated the optimum amount of fertilizer nitrogen found in 8 independent multi-level fertilizer nitrogen trials. A fixed rate of 100-125 kg of nitrogen ha^{-1} yielded better results. The possible reasons for the absence of a strong relationship between the amount of soil mineral nitrogen before sowing and the optimum amount of nitrogen fertilizer are discussed.

Keywords: nitrogen fertilizer recommendation, soil mineral nitrogen, onions

Introduction

In the Netherlands nitrogen fertilizer recommendations for most arable crops are based on soil mineral nitrogen before sowing or planting. These recommendations are based on a number of multi-level fertilizer nitrogen trials. At each trial, soil mineral nitrogen was measured at the end of winter or in early spring and the economically optimum nitrogen fertilizer application rate was assessed. The nitrogen fertilizer recommendations are based on the linear relationship between soil mineral nitrogen and the optimum nitrogen fertilizer application rate (Ris *et al.*, 1981; Neeteson, 1990). This relationship offers a means to improve the tuning of nitrogen supply to crop demand.

The optimum fertilizer nitrogen application rate for onions is subject to large variation. Böttcher & Kolbe (1975) found optimum nitrogen application rates in literature to vary between 45 and 190 kg ha^{-1}. Their own trials resulted in optimum application rates of 20, 40 and 80 kg ha^{-1}. Smoter & Nowosielski (1973) found optimum nitrogen application rates ranging from 0 to 350 kg ha^{-1}. Maier *et al.*, (1992) found an optimum of 300 kg N ha^{-1} in two trials. In trials in the Netherlands with onions maximum yield was reached at nitrogen application rates varying between 150 and 300 kg ha^{-1} (Greenwood *et al.*, 1992)

In Germany, soil mineral nitrogen before sowing or planting of onions is included in the fertilizer nitrogen recommendations (Lang, 1988; Wehrman & Scharpf, 1986). However, the relationship between soil mineral nitrogen and optimum nitrogen application rates in onions and the degree of variation in optimum nitrogen application rates has not been published. In this paper this relationship was studied with results obtained in multi-level fertilizer nitrogen trials with onions grown from seed. The data obtained were analyzed according to two different statistical methods.

Materials and methods

In the period 1978–1982 36 trials have been conducted in which the effect of fertilizer nitrogen application rates on yield of spring sown onions were studied. The number of trials per year varied from 5 to 11. The trials were located in the main onion growing areas in the Netherlands and were all situated on clay or sandy clay soils. In each trial plots received either 0, 50, 100, 150 or 200 kg ha^{-1} nitrogen as calcium ammonium nitrate fertilizer before sowing. There were always three replicates in a randomized block design. Because data per plot were not available for all trials, the data were averaged over replications. Onions were sown between April 7 and May 8. The average plant density on untreated plots in June was 108 plants m^{-2} (s.d. = 33). Harvest took place between September 9 and October 26, on average 173 days after sowing. Average maximum and minimum yield of the 36 trials amounted to 65 (s.d. = 11) and 56 (s.d. = 12) t ha^{-1}. Average maximum yields in the successive years were 69, 64, 50, 71 and 64 t ha^{-1}. The varieties used were Hyduro and the Rijnsburger selections Barko, Jumbo, Wijbo and Balstora. The amounts of soil mineral nitrogen in the layers 0–30 cm and 30–60 cm were determined before sowing and also during growth of the crop. The latter was carried out on the plots that had received no nitrogen. Soil sampling before sowing took place between February 19 and April 17, on average 28 days before sowing. Soil sampling during crop growth took place between May 30 and July 9, on average 63 days after sowing. In 1982 the nitrogen content of the bulbs was determined in 7 trials. Statistical analyses were performed with Genstat 5, Release 3.1 (Payne *et al.*, 1993).

Method A

The amount of fertilizer nitrogen at maximum yield was estimated individually for each trial on the basis of a quadratic response function or a linear exponential function according to Neeteson & Wadman (1987). Of both functions the physical rather than the economical optimum was determined, because of the large fluctuations in the market price of onions and the relatively small contribution of nitrogen fertilizer to the total growing costs of onions in the Netherlands. The quadratic response function has the form of:

$$y = \beta_0 + \beta_1 N + \beta_2 N^2 \tag{1}$$

where y is the yield in t ha^{-1}, N is the applied fertilizer nitrogen in kg ha^{-1} and β_0, β_1 and β_2 are parameters that were estimated using linear regression analysis. The optimum amount of fertilizer nitrogen, N_{opt} equals:

$$N_{opt} = - b_1 / 2b_2 \tag{2}$$

where b_1 and b_2 are estimates of the parameters β_1 and β_2. The linear exponential function has the form:

$$y = \beta_0 + \beta_1 e^{\alpha N} + \beta_2 N \tag{3}$$

where α, β_0, β_1 and β_2 are parameters that were estimated using nonlinear regression analysis. N_{opt} can be calculated according to:

$$N_{opt} = \ln (-b_2 / ab_1) / a \tag{4}$$

where a, b_1 and b_2 are estimates of the parameters α, β_1 and β_2. The optimum amount of fertilizer nitrogen calculated for each trial was related by linear regression analysis to the N_{min} observed in each trial according to:

$$N_{opt} = \mu - \delta N_{min} \tag{5}$$

where the parameter μ (the intercept of the regression of N_{opt} on N_{min}) indicates the N_{opt} at $N_{min} = 0$ and δ (the regression coefficient of N_{opt} on N_{min}) indicates the efficiency of the N_{min} relative to fertilizer nitrogen. In the analysis a weight factor per trial was included that was the reciprocal value of the residual variance of the analyses per trial with model (1). By doing so the trials with less variation determined the regression to a larger extent. The recommended amount of fertilizer N for trial i ($N_{rec,i}$) can be now calculated by:

$$N_{rec,i} = m - dN_{min,i} \tag{6}$$

where m and d are estimates of μ and δ respectively.

Method B

In the second method the available data were analysed together as was done by

Neeteson & Zwetsloot (1989) using a linear exponential equation. But rather than fitting the equation to the within-block variation of various multi-level fertilizer nitrogen trials as was done by Neeteson & Zwetsloot (1989), we fitted the equation to the mean yield data per fertilizer level per trial according to:

$$y = \beta_{0,i} + \beta_1 e^{\alpha N_{tot}} + \beta_2 N_{tot} \tag{7}$$

$$N_{tot} = N + \delta N_{min,i} \tag{8}$$

where $\beta_{0,i}$ is the intercept for trial i. The parameters of (7) and (8) were estimated using non-linear regression analysis. Equation (7) implies that the optimum value of N_{tot} (N_{topt}) is the same in all trials. This amount can be calculated according to equation (4) using the estimated values of the parameters in (7). N_{rec} for trial i can now be calculated as:

$$N_{rec,i} = N_{topt} - dN_{min,i} \tag{9}$$

where N_{topt} equals the parameter m in equation (6) and d is the estimate of δ in (8). In the text the value of N_{topt} will be represented as m.

Method B was also used after replacing the linear exponential model by a quadratic model:

$$y = \beta_{0,i} + \beta_1 N_{tot} + \beta_2 N_{tot}^2 \tag{10}$$

where N_{tot} is calculated according to (8).

The optimum value of N_{tot} (N_{topt}) and the N_{rec} for each trial resulting from this quadratic equation can be calculated on the basis of equations (2) and (9). The analyses of equations (7) and (10) were performed with the reciprocal of the residual variance of the analysis per trial with model (1) as a weight factor.

The predictive value of equations (6) and (9) were verified using data of 8 independent multi-level fertilizer nitrogen trials of which the amount of mineral nitrogen was measured in the soil before sowing in the layers 0–30 and 0–60 cm (Table 1). For each of these trials the optimum amount of nitrogen fertilizer was calculated using equation (1). The trials were conducted in the period between 1975 and 1993.

Results

Method A

N_{opt} could be estimated with the quadratic response function in 26 of the total of 36 trials. The results showed 7 trials of which the estimate b_2 had a positive sign which resulted in an optimum indicating a minimum yield level and 3 trials of which the calculated optimum (225, 244 and 738 kg N ha^{-1}) fell outside the studied range

Table 1. Nitrogen range tested, observed yield range (t ha^{-1}), plant density (m^{-2}), sowing and harvest date, N_{min} observed in the layers 0–30 and 0–60 cm before sowing and cultivar used in the verification trials. All data are taken from unpublished sources.

Year of the trial	N-range tested	Yield range	Plants (m^{-2})	Sowing date	Harvest date	N_{min} (kg ha^{-1})		Cultivar
						0–30	0–60	
1975	0–160	29–59	168	27/4	3/10	17	35	Rivato[1]
1977	0–160	70–72	106	26/3	10/10	23	71	Jumbo[1]
1985	50–200	72–76	90	12/4	24/9	25	29	Hyton
1986	50–200	88–96	85	19/4	16/9	16	23	Hyton
1992	0–150	69–75	87	21/4	1/9	21	71	Hysam
1992	0–150	39–63	40	23/4	16/9	17	34	Hysam
1993	0–150	66–75	80	9/4	7/9	13	21	Hysam
1993	0–150	56–70	67	13/4	20/9	14	28	Hysam

[1] Rivato and Jumbo are selections of the Rijnsburger variety.

(0–200 kg N ha^{-1}) and is thus an extrapolated value. For these reasons the data from these trials were omitted. The calculated values of N_{opt} averaged 128 (s.d. = 43) kg N ha^{-1} and ranged from a minimum of 19 to a maximum of 199 kg N ha^{-1}. In the following they are referred to as the observed optimum amounts of fertilizer nitrogen. These optima were related to the N_{min} before sowing and during crop growth in May/June on the untreated plots in the layers 0–30 and 0–60 cm. Although it has no practical value to relate the N_{min} during crop growth to the N_{opt}, the relation was studied because the N_{min} during crop growth gives more information on the amount of nitrogen available to the crop due to mineralization than the N_{min} before sowing. The average N_{min} values found in the layers 0–30 and 0–60 cm before sowing were 27 and 53 kg N ha^{-1} with standard deviations of 12 and 24 kg N ha^{-1}. The N_{min} in June in both layers averaged 74 (s.d. = 27) and 117 (s.d. = 41) kg N ha^{-1} respectively.

The parameters in equation (6) for both soil layers and observation moments of N_{min} are shown in Table 2. The value of d was significantly larger than 0 only when the N_{min} before sowing in the layer 0–30 cm was considered. With equation (6) N_{rec} can be calculated for each trial on the basis of the N_{min}. The recommended values were compared with the observed optimum values. Also, the yield that would have resulted from N_{rec} when this amount would have been applied in each of the trials

Table 2. Value of the parameters m and d in equation (6) and deviations of recommended (N_{rec}) from observed optimum values (N_{opt}) of fertilizer nitrogen and the corresponding yield (Y_{rec} resp. Y_{max}) on the basis of the quadratic model in Method A. Standard deviations between parentheses.

Time of N_{min}	Layer (cm)	m (kg ha^{-1})	d (–)	N_{rec}-N_{opt} (kg ha^{-1})	Y_{rec}-Y_{max} (t ha^{-1})
Before sowing	0–30	191 (23)	2.21 (0.75)	3 (46)	−0.8 (1.2)
	0–60	159 (26)	0.59 (0.46)	1 (45)	−0.6 (0.8)
June	0–30	163 (31)	0.45 (0.37)	3 (42)	−0.5 (0.5)
	0–60	137 (30)	0.08 (0.23)	1 (43)	−0.5 (0.5)

(Y_{rec}), was calculated using equation (1) and was compared with the yield at the observed optimum nitrogen level (Y_{max}). The results of both comparisons are listed in Table 2. On average N_{rec} practically equals the observed N_{opt} as could be expected. The large variation of the estimates m and d is reflected in the large variation of the deviations. However, deviations from Y_{max} varied to a lesser extent. The number of trials with a deviation of 30 kg N ha^{-1} or more between N_{rec} and N_{opt} varied between 12 and 14 of the 26 trials, depending on the time and layer of soil analysis. Deviations of the corresponding yields that were larger than 1 t ha^{-1} were found in a number of trials varying between 4 and 5.

The linear exponential curve could only be fitted in 14 trials. Of these, the quadratic curve could be fitted in 11 trials. The mean value of N_{opt} of these 11 trials was 104 (s.d. = 44) kg ha^{-1} when using the linear exponential model and 115 (s.d. = 33) kg ha^{-1} when using the quadratic curve. The standard deviation of the difference (11 kg N ha^{-1}) was 16 kg N ha^{-1}. Neeteson & Wadman (1987), working with sugar beet and potatoes, found that N_{opt} was lower when estimated with the quadratic model than with the linear exponential model. This finding could therefore not be confirmed by our results. However, the average residual mean square for the quadratic model based on 11 trials amounted to 2.26 and for the linear exponential model to 1.73. This finding is in accordance with the slightly lower residual sums of squares after applying the linear exponential model compared to the quadratic model as found by Neeteson & Wadman (1987). Because of the low number of trials with which the linear exponential model could be fitted and the absence of a significant difference in the value of N_{opt} with the quadratic model, further calculations with the linear exponential model in Method A were not performed.

Method B

The results from the calculations with the quadratic and the linear exponential model based on the same 26 trials that were used with Method A are summarized in Table 3. In addition, the residual sums of squares (RSS) of both models are listed in Table 4, together with the RSS of the models when the parameter d (9) was assumed to be zero. Comparisons with the latter give information on the extent to which the RSS is lowered by taking N_{min} into account. The overall results of the calculations with Method B are similar to the results with the quadratic model and Method A (Table 2). Again, the N_{min} before sowing in the soil layer 0–30 cm gives the best fit and the highest value of d. As was found with Method A, the deviation between N_{rec} and observed N_{opt} showed large variation, while yield deviations were relatively small. However, the linear exponential model seemed to underestimate the observed optimum amount of fertilizer N slightly, whereas the quadratic model overestimated this amount to a small extent. According to the quadratic model the difference between N_{rec} and the observed N_{opt} was larger than 30 kg ha^{-1} in 11 to 14 of the 26 trials depending on the set of N_{min} values used. For the linear exponential model these figures ranged from 12 to 14. Yields deviated more than 1 t ha^{-1} in 5 or 6 of the 26 trials using the linear exponential model and in 4 or 5 of the trials using the quadratic model.

Table 3. Values of the parameters m (= N_{topt}) and d in equation (9) and deviations of recommended (N_{rec}) from observed optimum values (N_{opt}) of fertilizer nitrogen and the corresponding yield (Y_{rec} resp. Y_{max}) on the basis of Method B. Standard deviations between parentheses.

Time of N_{min}	Layer (cm)	m (kg ha^{-1})	d (–)	N_{rec}-N_{opt} (kg ha^{-1})	Y_{rec}-Y_{max} (t ha^{-1})
linear exponential model					
Before sowing	0–30	181 (18)	2.18 (0.46)	–6 (45)	–0.8 (1.0)
	0–60	148 (16)	0.43 (0.23)	–3 (44)	–0.6 (0.6)
June	0–30	170 (20)	0.63 (0.19)	–3 (42)	–0.5 (0.5)
	0–60	144 (18)	0.16 (0.11)	–3 (43)	–0.5 (0.5)
quadratic model					
Before sowing	0–30	187 (15)	2.01 (0.43)	4 (45)	–0.7 (1.1)
	0–60	151 (14)	0.40 (0.22)	2 (44)	–0.6 (0.7)
June	0–30	175 (17)	0.58 (0.19)	5 (42)	–0.5 (0.5)
	0–60	146 (16)	0.14 (0.11)	3 (43)	–0.5 (0.6)

Table 4. Residual sums of squares (RSS) of the quadratic and the linear exponential model based on Method B using either the N_{min} before sowing or the N_{min} in June in the layers 0–30 and 0–60 cm.

Time	Layer (cm)	RSS	
		quadratic model	linear exponential model
No N_{min}		1471	1468
Before sowing	0–30	1114	1069
	0–60	1421	1416
June	0–30	1316	1294
	0–60	1447	1440

Comparison with fixed nitrogen fertilization rates

As a comparison the yield was calculated that would have been reached if fixed rates of N would have been applied in the 26 trials. The results are listed in Table 5. From 128 kg of nitrogen ha^{-1} downwards, a decreasing amount of fertilizer lead to an increasing average deviation from Y_{max}. At rates of 100, 125 and 150 kg ha^{-1} the average deviations from Y_{max} were comparable to the average deviations from Y_{max} mentioned in Tables 2 and 3. However, the number of trials which showed deviations of more than 1 t ha^{-1} seemed somewhat larger. Compared to the observed N_{opt} in each of the 26 trials, an advise of a fixed rate of 100 kg N ha^{-1} would have resulted on average in 28 kg ha^{-1} less nitrogen given with a low but not significant deviation from Y_{max}. In 9 trials this deviation would have been more than 1 t ha^{-1}.

Table 5. Deviations of fixed nitrogen application rates (N_{rec}, kg ha^{-1}) from observed optimum values (N_{opt}) of fertilizer N, corresponding yield difference (Y_{rec} resp. Y_{max}) and number of the 26 trials with deviations larger than 30 kg N ha^{-1} or 1 t ha^{-1}. Standard deviations between parenthesis.

Fixed N rate (kg ha^{-1})	N_{rec}-N_{opt}	Y_{rec}-Y_{max}	Trials with deviations	
			>30 kg N ha^{-1}	>1 t ha^{-1}
0	–128 (43)	–7.6 (5.1)	25	25
50	–78 (43)	–3.2 (2.5)	23	18
75	–53 (43)	–1.7 (1.6)	21	14
100	–28 (43)	–0.9 (0.8)	15	9
125	–3 (43)	–0.5 (0.5)	14	6
150	22 (43)	–0.7 (1.0)	12	6
175	47 (43)	–1.5 (1.7)	17	13
200	72 (43)	–2.8 (2.5)	21	19

Influence of yield level

In Method B it is assumed that the total optimum amount of nitrogen is independent of the yield level, because the parameters in equations (7) and (10) that are needed to calculate the optimum amount of nitrogen were independent of the trial. However, it can be argued that crops grown under circumstances with high yield potential need more nitrogen than crops grown under circumstances with less yield potential. To integrate this effect in the relation between N_{min} and N_{opt} the following calculations were made. First the yields per trial and per fertilizer level were lowered with the difference between the maximum yield of each trial and 50 t ha^{-1}, which is a realistic yield level of spring sown onions in the Netherlands. This difference was multiplied by the average nitrogen content measured at maximum yield in the bulbs at harvest in 7 trials in 1982 (1.92 g N kg^{-1} fresh yield; s.d. = 0.16). The result of this multiplication was subtracted from the applied nitrogen rates. The same calculations as performed on the original data were done with these modified data. The residual sums of squares using the linear exponential model in Method B decreased only to a small extent. When N_{min} was not used the RSS decreased from 1468 (Table 4) to 1360. When the N_{min} was incorporated in the model the values for the RSS were 1035, 1293, 1183 and 1309 respectively for the layers 0–30 and 0–60 cm before sowing and in June. However, the results in terms of the deviations of N_{rec} from observed N_{opt} and corresponding yield with this modified data-set were not better than the results already reached (Tables 2 and 3). Average deviations were similar while variations remained large.

Verification results

The optimum amounts of nitrogen fertilizer in the verification trials were compared to the recommended amounts and to fixed rates of nitrogen fertilizer (100 and 125 kg ha^{-1}). The optimum amounts were calculated for each trial with the quadratic model (observed N_{opt}). The recommended nitrogen fertilizer rates (N_{rec}) were calcu-

Table 6. Deviations of recommended (N_{rec}) from observed values (N_{opt}) for optimum nitrogen fertilizer and corresponding yield (Y_{rec} resp. Y_{max}) of the verification trials depending on the soil layer and set of regression constants based on N_{min} before sowing as listed in Tables 2 and 3. Standard deviations between parenthesis.

Regression constants	Layer (cm)	N_{rec}-N_{opt} (kg ha^{-1})	Y_{rec}-Y_{max} (t ha^{-1})
Method A, quadratic curve	0–30	37 (25)	–2.3 (3.0)
	0–60	23 (23)	–1.3 (1.8)
Method B, quadratic curve	0–30	37 (24)	–2.2 (2.9)
	0–60	22 (22)	–1.2 (1.6)
Method B, linear exponential curve	0–30	28 (24)	–1.6 (2.2)
	0–60	17 (22)	–1.0 (1.3)
No N_{min} used, fixed rate 100 kg N ha^{-1}	–	–13 (20)	–0.6 (1.1)
No N_{min} used, fixed rate 125 kg N ha^{-1}	–	12 (20)	–0.7 (0.8)

lated using the estimates for the regression coefficients μ and δ as mentioned in Tables 2 and 3. Only the N_{min} before sowing was considered. Y_{max} (yield at N_{opt}) and Y_{rec} (yield at recommended fertilizer rate) were calculated as explained before. The average deviations of the recommended or fixed rates from the observed optimum N are mentioned in Table 6. These deviations were larger than the ones mentioned in Tables 2 and 3 and point to an overall overestimation of the nitrogen needed to give the highest yields when advice is based on soil mineral nitrogen. Fixed rates of 100 or 125 kg N ha^{-1} on average slightly under- or overestimated the nitrogen needed to give the optimum yield. The yield depressions that would have resulted from applying the recommended amount of fertilizer nitrogen based on N_{min}, seem larger than the yield depressions mentioned in Tables 2 and 3. Average deviations from Y_{max} resulting from a fixed rate of either 100 or 125 kg N ha^{-1} are comparable to the ones mentioned in Table 5.

Discussion

The poor relationship between the mineral nitrogen in the soil before sowing and the optimum amount of fertilizer nitrogen before sowing and the results of the calculations based on fixed nitrogen application rates, lead to the advice for Dutch onion growers to apply 100 to 120 kg N ha^{-1} before sowing irrespective of the N_{min} before sowing. Some explanations for the finding that little or no variation found in the optimum amount of fertilizer nitrogen could be explained by the amount of mineral nitrogen in the soil before sowing, are possible.

The first explanation could be that the onions have a low initial growth rate (Brewster, 1979), and therefore a low demand for nitrogen in the beginning of growth. The period between sowing (beginning of April) and at the onset of rapid increase in biomass of the onion crop can last up to 60 days or more (De Visser, 1993). At the end of this period the amount of mineral nitrogen in the soil will have changed due to mineralization, denitrification or leaching beyond the rooting zone.

Then it could be expected that the amount of mineral nitrogen at the end of May or in the beginning of June would explain a larger part of the variation in the optimum amount of fertilizer N. However, the results showed no improvement of the relationship when the amounts of mineral N before sowing were replaced by the amounts found in May/June. Possibly, relating the soil mineral nitrogen in June to the optimum nitrogen fertilizer applied in May/June, would yield better results. In our trials the amount of fertilizer nitrogen applied before sowing will not have been available in May/June in the same amount due to denitrification or leaching beyond the rooting zone.

A second possible explanation for the absence of a strong relationship could have been the variation in yield level and thus the variation in nitrogen demand by the crop (Neeteson, 1990). Lang (1988) advised to fertilize onions 15–20 kg N ha^{-1} more or less per 10 t ha^{-1} more or less yield. However, accounting for yield level did not improve the relationship. A third possible explanation could be that part of the variation originates from the determination of the optimum amount of fertilizer nitrogen in each trial, as was found by Neeteson & Wadman (1987) in trials with 7 levels of nitrogen application. In our trials only 5 levels were used, so the variation of the calculated optimum amount of fertilizer nitrogen could have been even larger. A further explanation for the poor relationship between N_{min} before sowing and the optimum N application rate could be the relatively low variation in the N_{min} found (standard deviation = 12 kg N ha^{1}).

The results showed that the amount of mineral nitrogen in the soil in the layer 0–30 cm explained more of the variation in the optimum amount of fertilizer N than the amount in the layer 0–60 cm. This can be explained from the shallow root system of onions. Greenwood *et al.*, (1982) found that 90% of the root system of onions was found in the upper 18 cm of the soil during a large part of the growing season. This rooting pattern is a consequence of the continuous formation of new shoot-borne roots that show only limited branching (DeMason, 1990; Greenwood *et al.*, 1982). This would imply that as soon as most of the nitrogen fertilizer is transported below the 18 cm soil depth, the onion plants would have to depend on mineralized nitrogen to a larger extent to fullfill their nitrogen demand. Indeed, Greenwood *et al.*, (1989) found that the apparent recovery of fertilizer nitrogen of onions at an infinitely small amount of fertilizer nitrogen was 31%, which was low in comparison to other crops with a longer or equal length of the growing season. This phenomenon could also partly explain the poor relationship between N_{min} and N_{opt}.

On average the yield difference per trial between the maximum observed yield and the yield at zero fertilizer nitrogen was only 12%, while 88% of the 36 trials showed a difference of less than 20%. A low apparent recovery of fertilizer N of onions, as found by Greenwood *et al.*, (1989), could have contributed to the observed weak response to fertilizer N. This would imply that the soil mineralization during the growing season met the crop demand for nitrogen to a large extent. A low response to nitrogen applied before sowing gives a rather flat response curve of which the determination of the optimum fertilizer nitrogen is more difficult and is thus interfering with the relation between N_{min} and N_{opt}.

Yield depressions at higher nitrogen application rates, as observed in part of our trials, were also observed by others (Böttcher & Kolbe, 1975; Amans & Slangen, 1994; Hamilton *et al.*, 1978). According to Amans and Slangen (1994) and Greenwood *et al.*, (1992) yield depressions of onions at high fertilizer level can originate from the salt effects that are toxic to young onion plants. This can lead to fewer plants and a slower initial growth rate. In our trials the plant density (m^{-2}) on average declined from 103 at zero fertilizer to 95 at 200 kg N ha^{-1}. Calculations with an onion growth model (De Visser, 1993) showed that such a difference in plant density will not lead to yield depressions in the order of 5 to 10% as observed in our trials due to high nitrogen fertilization. However, calculations with the onion growth model showed that 10% decrease in the initial relative growth rate decreases final yield by 3%.

From Tables 2 and 3 it is clear that the different methods to establish a relation between N_{min} and N_{opt}, showed comparable differences between recommended and observed optimum amount of fertilizer N and corresponding deviations from Y_{max}. Using Method B the linear exponential model could be preferred on the basis of the lower residual sums of squares (Table 4). Neeteson & Wadman (1987) also found lower residual sums of squares using the linear exponential model compared to the quadratic model. The verification results (Table 6) show that the linear exponential model is slightly, although not significantly, better than the quadratic model. Nevertheless, independent of the calculation method or the model used, too much nitrogen would have been advised and deviations from Y_{max} would have been detected that were larger than the deviations mentioned in Tables 2 and 3. Comparing Tables 5 and 6 learns that the optimum fixed rate of fertilizer nitrogen in the 8 verification trials is lower than in the original 26 trials. However, the current advice of a fixed rate of 100 to 120 kg of nitrogen ha^{-1} still seems to be appropriate.

The results clearly show that using the soil mineral nitrogen before sowing will not contribute to optimize the advised N application rate in relation to yield. An optimization of the N application rate in relation to nitrogen leaching or the amount of nitrogen left in the soil after harvest was not subject of this study. If the calculated yield at the advised fixed fertilizer N application rate of 100 kg ha^{-1} in each of the 26 trails is multiplied by the observed nitrogen content at the same nitrogen application rate found in 7 trials in 1982 (1.93 g N kg^{-1} fresh yield; s.d. = 0.19), the amount of nitrogen taken up by the crop at harvest can be estimated to have been 129 (s.d. = 21) kg N ha^{-1} on average. The nitrogen amount taken up at 0 kg N ha^{-1} can be estimated to have been 97 (s.d. = 16) kg N ha^{-1} after multiplying the observed mean nitrogen content on the untreated plots in the same 7 trials in 1982 (1.61 g N kg^{-1} fresh yield; s.d. = 0.25) by the calculated yield at 0 kg N ha^{-1} in each of the 26 trials. This would mean that the apparent recovery rate of the fertilized nitrogen at a rate of 100 kg N ha^{-1} had been 32%, which is only slightly higher than the maximum apparent recovery rate of 31% found by Greenwood *et al.*, (1989). On average, at a fixed rate of 100 kg N ha^{-1} 68 kg N ha^{-1} would be subject to leaching during and after crop growth. On average, at higher N application rates the apparent recovery rate will propably decrease because luxury consumption of nitrogen by onions is small (Greenwood *et al.*, 1992) and yields are not likely to increase (Table 5). Therefore, it seems necessary to maximize the apparent recovery rate of the nitrogen applied to the crop to minimize risk of nitrate loss to the environment. Based on a study into the rooting characteristics and nitrogen utilisation of leeks that (like onions) have a shallow rooting system and take up most of the nitrogen in the second part of the growing season, Smit *et al.*, (1995) suggested that nitrogen should become gradually available to this crop as the season progresses in order to minimize nitrogen leaching. Therefore, it can be expected that an advisory system based on split nitrogen dressing, as described by Lang (1988), will improve the apparent recovery rate of onions and thereby minimize the risk of nitrogen leaching. At the same time yield can be expected to be optimal, because the shallow rooting system of onions would allow the crop to take up fertilizer nitrogen supplied during the growing season shortly after application, provided rain or irrigation will dissolve the nitrogen.

According to the advisory system described by Lang (1988), the soil is sampled once before sowing and once or twice after emergence. After each sampling date the crop is supplied with the amount of nitrogen that is needed until the next sampling date or until harvest. In this way net mineralization during the growing season can be taken into account. This advisory system will lead to a small amount of nitrogen fertilization before sowing, because of the low demand of the crop during early growth. Possibly, a row application of this amount could improve its effectiveness and would thereby further improve apparent recovery rate. Research to study split nitrogen dressing in combination with nitrogen row application was carried out between 1992 and 1994. The results will be published later.

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