J. J. Neeteson

Assessment of fertilizer nitrogen requirement of potatoes and sugar beet

Proefschrift
ter verkrijging van de graad van
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te Wageningen

Abstract

This thesis includes six papers on the assessment of fertilizer nitrogen requirement of potatoes and sugar beet. The aim of the investigations described is to improve fertilizer nitrogen recommendations in such a way that high crop yields of a good quality can be obtained while detrimental effects of fertilizer nitrogen application on the environment are minimized.

Yield response curves of numerous fertilizer nitrogen trials with potatoes and sugar beet could be described adequately by a modified exponential equation. However, the magnitude of the confidence interval for the economically optimum application rates, as calculated from the response curves, was frequently very high. In 60 % of the potato trials and in 46 % of the sugar-beet trials it was higher than 300 kg N per ha.

A statistical analysis revealed that the response of potatoes and sugar beet to fertilizer nitrogen depended on the amount of mineral nitrogen already present in the soil at the end of winter, the soil type, and presence or absence of organic manures applied previously. The performance of the current Dutch nitrogen fertilizer recommendations, which take only the amount of soil mineral nitrogen present at the end of winter into account, was compared with that of recommendations which also take soil type and recent applications of organic manures into account. On average, smaller amounts of fertilizer nitrogen were recommended according to the current method, but the yields obtained with both methods were similar. The current recommendation method is therefore preferable to the refined method.

When it is assumed that the probability of a yield deficit larger than 5 % is not allowed to exceed 5 %, the currently recommended fertilizer nitrogen application rate for potatoes can be reduced by 25 %, but the rate for sugar beet cannot be lowered. The effect of a change in the ratio of cost of fertilizer nitrogen to price of crop produce was much larger for potatoes than for sugar beet. A fivefold increase in the ratio, for instance due to a levy imposed on fertilizers, decreased the optimum for potatoes by 50 %, but for sugar beet by only 20 %. However, it also considerably decreased farm income, especially in the case of potatoes.

A dynamic model for the response of potatoes to fertilizer nitrogen is described, the inputs of which are generally available to growers. The model was used to predict the effects of seven levels of fertilizer nitrogen on tuber yield in 61 experiments. When only the input data were used that were available at the time when advice is required, the model correctly predicted the optimum fertilizer nitrogen rate in 84 % of the experiments. This result is about as good as that obtained with the current recommendation method. When it will be possible to reliably predict the mineralization rate at individual sites, it is expected that the model will provide a better basis for practical advice than is available at present.

With the model it was calculated that in normal and wet springs, nitrate leaching always occurs. The nitrate leached did not originate from soil nitrogen mineralized in spring or from applied fertilizer, but from mineral nitrogen present in the 30-60 cm soil layer at the end of winter. The total losses of nitrogen, i.e. the amount of nitrate lost due to leaching in spring plus the amount of soil mineral nitrogen accumulated at the time of harvest of potatoes, were similar in a loamy sand and a clay loam. The larger loss by leaching from the sand was offset by the larger accumulation of mineral nitrogen in the loam. It was concluded that little nitrate leaching occurs when the current nitrogen fertilizer recommendations are followed, provided that mineralization in the soil proceeds at an average rate.

Promotor: dr. ir. A. van Diest
hoogleraar in de bodemvruchtbaarheid en bemesting

Co-promotor: dr. ir. M. L. van Beusichem
universitair hoofddocent bij de vakgroep Bodemkunde en Plantevoeding

Assessment of fertilizer nitrogen requirement of potatoes and sugar beet

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STELLINGEN

1. Wanneer de huidige adviezen voor de stikstofbemesting van aardappelen met 25 procent verlaagd worden, zal de opbrengstderving gering zijn. Bovendien zal dan de kans gering zijn dat de EG-norm voor de maximaal toelaatbare nitraatconcentratie in grondwater dat dient voor drinkwater wordt overschreden.
   Dit proefschrift.

2. Het is te verwachten dat in de akkerbouw een heffing op het gebruik van kunstmeststikstof geen ander effect zal hebben dan verslechtering van de financiële positie van de akkerbouwer.
   Dit proefschrift.

3. De optimale gift aan kunstmeststikstof, bepaald op een proefveld, is een slechte maat voor de behoefte van het op dat proefveld geteelde gewas aan kunstmeststikstof.
   Dit proefschrift.
   Sutherland, R.A., C.C. Wright, L.M.J. Verstraeten & D.J. Greenwood, 1986. The deficiency of the 'economic optimum' application for evaluating models which predict crop yield response to nitrogen fertiliser. Fertilizer Research 10: 251-262.

4. Indien in de geïntegreerde akkerbouw aan minimalisering van de milieu-effecten van bemesting een hogere prioriteit wordt gegeven dan aan vermindering van het dierlijke-mestoverschot in Nederland, dient bemesting met kunstmest de voorkeur te hebben boven bemesting met dierlijke mest.
   Vereijken, P.H. & H.G. van der Meer, 1988. Geïntegreerde bemesting: onbekend maakt onbemind? Landbouwkundig Tijdschrift 100 (11): 19-22.

5. In het bemestingsonderzoek is de term 'minerale stikstof' ingeburgerd. Het verdient aanbeveling deze te vervangen door 'anorganische stikstof'.

6. Het traditionele bemestingsonderzoek heeft goede bemestingsadviezen opgeleverd voor het behalen van hoge gewasopbrengsten, maar is ontoereikend voor het voorspellen van de milieu-effecten van bemesting.

7. De melkprijs - de prijs die de melkveehouder voor de op zijn bedrijf geproduceerde melk krijgt - dient hoger te zijn naarmate het vetgehalte van de melk lager is, het eiwitgehalte hoger is en het eiwit voor een groter gedeelte uit voor de kaasproduktie geschikte κ-caseïne bestaat.

8. 'Overbemesting' bij wintertarwe is meestal geen overbemesting.

9. Het is onafwendbaar dat 'referees' verbonden aan internationale wetenschappelijke tijdschriften binnen afzienbare termijn een telefax ter beschikking hebben.
Anon., 1989. Nature statistics. Nature 337:409.

10. De Landbouwuniversiteit Wageningen lijkt goed geëquipeerd te zijn om onderzoek te verrichten naar het bestrijden van computervirussen. Zij beschikt immers over de vakgroepen Informatica en Virologie.

11. Het is niet terecht als Nederlandse kaas in West-Duitsland het predikaat 'das ist Käse' zou krijgen.

12. Het is goed ze te hebben, maar het is beter er te wonen.

Stellingen behorend bij het proefschrift 'Assessment of fertilizer nitrogen requirement of potatoes and sugar beet'.
J.J. Neeteson, Wageningen, 2 augustus 1989.

Aan de nagedachtenis van mijn vader

Curriculum vitae

Jacques J. Neeteson werd op 17 juni 1954 geboren te Utrecht. Na de lagere school begon hij in september 1966 met de middelbare-schoolopleiding op het Utrechts Stedelijk Gymnasium. In juni 1972 behaalde hij het diploma gymnasium-β, waarna hij in september 1972 aanving met de studie aan de Landbouwhogeschool te Wageningen. In januari 1981 legde hij het doctoraalexamen in de landbouwwetenschappen, studierichting Landbouwplantenteelt, cum laude af. De doctoraalvakken waren de leer van het grasland (prof. ir. M. L. 't Hart, prof. ir. J. G. P. Dirven), de bodemvruchtbaarheid (prof. dr. ir. A. van Diest, dr. ir. M. L. van Beusichem), en de onkruidkunde (prof. dr. P. Zonderwijk, E. A. D. Baart). Per 1 mei 1981 trad hij als wetenschappelijk onderzoeker in dienst van het Instituut voor Bodemvruchtbaarheid (IB) te Haren (Gr.) met als hoofdtaak het verrichten van onderzoek naar de optimalisatie van de stikstofbemesting van akkerbouwgewassen. Vanaf 1 oktober 1987 is hij op het IB adjunct-hoofd van de afdeling Bemesting en Plantevoeding, en als zodanig verantwoordelijk voor het bemestingsonderzoek op het gebied van macronutriënten.

Woord vooraf

Bij het afronden van dit proefschrift, waarvoor het onderzoek verricht is op het Instituut voor Bodemvruchtbaarheid (IB) te Haren (Gr.), wil ik gaarne allen die op enigerlei wijze hebben bijgedragen aan de totstandkoming ervan hartelijk danken.

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De directeur van het IB, eerst ir. C. M. J. Sluijsmans en later dr. ir. K. Harmsen, wil ik gaarne bedanken voor de tijd en gelegenheid die het IB mij heeft geboden om dit proefschrift te voltooien.

Erg veel heb ik te danken aan de redactiecommissie van het IB, met name aan Cees Werkhoven voor het corrigeren van het Engels (soms op de meest onmogelijke tijdstippen!) en aan Wietse Wadman, Peter de Willigen, Rob Groot en Karl Dilz voor hun inhoudelijke kritiek. Hendrik Terburg (IB) wil ik gaarne danken voor zijn waardevolle adviezen betreffende de opmaak van het proefschrift in zijn geheel en van de erin voorkomende figuren in het bijzonder. Jimmy Robot, Menneke Bouwsema, Trea van der Velde en Annie Tuinman (IB) ben ik dankbaar voor hun hulp bij het gereedmaken van de manuscripten, en Pieter Oostra en Leen Muurmans (Pudoc) voor hun hulp bij het persklaar maken van dit proefschrift, voor het omslagontwerp en voor de contacten die zij met de drukker hebben onderhouden.

I am most grateful to Duncan Greenwood and Ann Draycott (Institute of Horticultural Research, Wellesbourne, UK) for their invaluable help and collaboration. I consider the five weeks I was able to spend at Wellesbourne in November-December 1986 as the most fruitful in my scientific life.

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Contents

Chapter 1

Introduction

Introduction

Nitrogen is essential for crop growth, because it is a constituent of both nonstructural (e.g. amino acids, enzymes, chlorophyll, nucleic acids) and structural (e.g. cell walls and membranes) components of the cell (Schrader, 1984). Nitrogen is taken up by plant roots from the soil solution mainly as ammonium or nitrate ions, but non-ionic nitrogen uptake by roots can also occur in the case of urea nutrition (van Beusichem & Neeteson, 1982). Mineral nitrogen, i.e. ammonium and nitrate, present in the soil solution originates from mineralized soil organic matter, inorganic and organic fertilizers, and wet and dry deposition from the atmosphere (Fig. 1). Since the annual contribution of atmospheric deposition to the nitrogen requirement of crops is generally less than 25 kg N per ha and that of mineralized soil nitrogen is about 100 kg N per ha, and there are inevitable nitrogen losses (Fig. 1), nitrogen fertilizers are applied to meet the total nitrogen requirement, which varies between about 200 kg N per ha for a crop such as oats and about 400 kg N per ha for intensively used grassland.

Russell (1914) probably was the first to recognize that soil mineral nitrogen affects the fertilizer nitrogen requirement of arable crops; after dry winters he found larger amounts of soil nitrate and higher yields of winter wheat than after wet win-

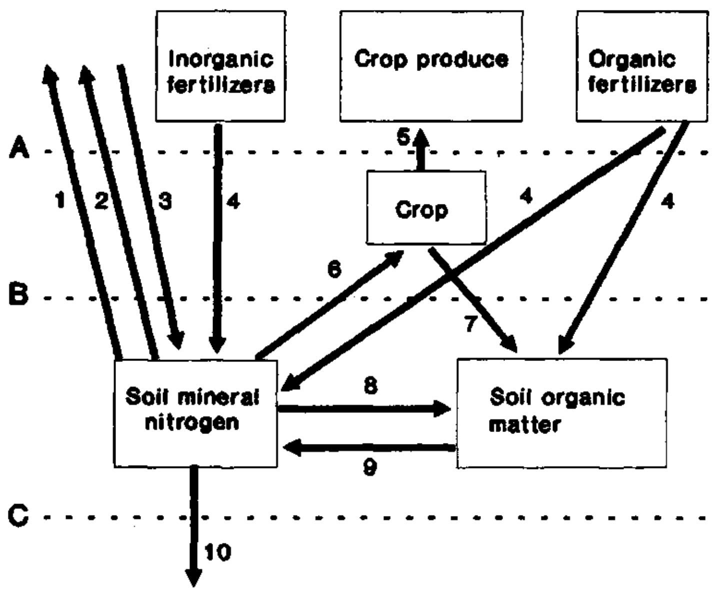

Fig. 1. Diagram of nitrogen fluxes in arable farming. 1 = denitrification; 2 = ammonia volatilization; 3 = atmospheric deposition; 4 = fertilization; 5 = harvest; 6 = crop uptake; 7 = crop residues; 8 = immobilization; 9 = mineralization; 10 = nitrate leaching. A – C = soil/crop system; B – C = root zone.

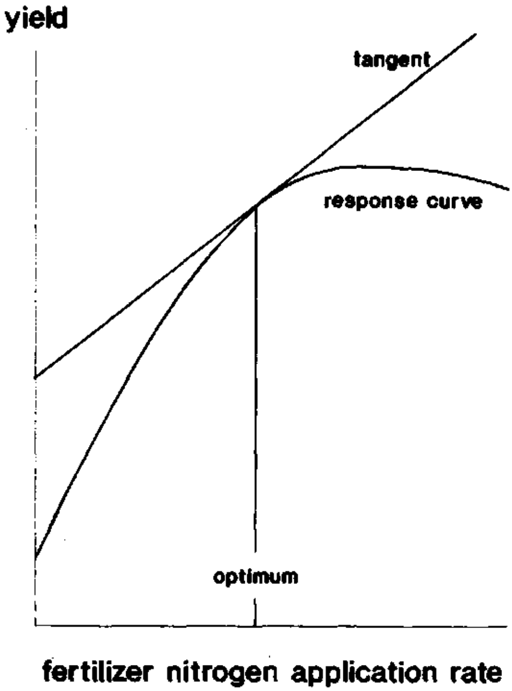

Fig. 2. Schematic presentation of the determination of the economically optimum application rate of fertilizer nitrogen from a response curve. The slope of the tangent reflects the ratio of the cost of fertilizer nitrogen to the price of crop produce.

ters. This was later confirmed by Boyd et al. (1957) for sugar beet. By covering parts of experimental fields during periods of rainfall, van der Paauw (1962) found that the weak response of potatoes and rye to added nitrogen after 'dry' winter periods could be attributed to the relatively large amount of mineral nitrogen present in the soil at the end of winter. After 'wet' winter periods, small amounts of soil mineral nitrogen were found, probably because nitrate was lost due to leaching. In the Netherlands these findings resulted in nitrogen fertilizer recommendations which were corrected annually for the amount of rainfall between 1 November and 1 March. For cereals it was recommended to increase the usual amount of fertilizer nitrogen by 10-30 kg per ha after wet winter periods, and to decrease it by the same amount after dry winter periods (van der Paauw, 1966).

To improve this indirect method of taking soil mineral nitrogen into account, research efforts were subsequently made to determine the relationship between soil mineral nitrogen at the end of winter and the optimum fertilizer nitrogen application rate for arable crops (Ris, 1974). For this purpose, large series of field experiments with winter wheat, potatoes and sugar beet were conducted for several years on various soil types in the Netherlands (Ris et al., 1981). In the experiments the amount of mineral nitrogen present in the soil at the end of winter was measured

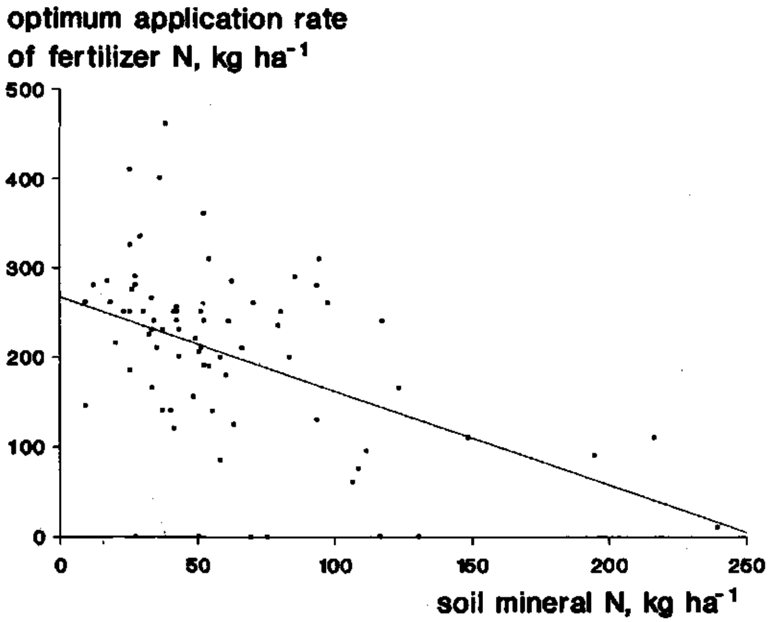

Fig. 3. Relationship between the amount of mineral nitrogen in the 0-60 cm soil layer at the end of the winter period and the economically optimum application rate of fertilizer nitrogen for potatoes on clay and loam soils. After Neeteson et al. (1984).

and various levels of fertilizer nitrogen were applied to determine the optimum application rate of fertilizer nitrogen. For each individual trial the economical optimum was determined from a hand-drawn yield response curve to which a tangent is drawn, the slope of which depends on the magnitude of the ratio of the cost of fertilizer nitrogen to the price of crop produce (Fig. 2).

As an example, the derivation of the current nitrogen fertilizer recommendation for potatoes on clay and loam soils (Neeteson et al., 1984) is shown in Fig. 3. The recommendation is based on 77 trials which were conducted in various regions in the Netherlands in the period 1973-1982. The relationship between the amount of mineral nitrogen in the 0-60 cm soil layer at the end of winter and the economically optimum application rate of fertilizer nitrogen is presented for all trials. The ratio of the cost of 1 kg fertilizer nitrogen and the price of 1 tonne crop produce was assumed to be 0.01 (Dfl. 2/Dfl. 200). The relationship between the amounts of soil mineral nitrogen present at the end of winter in the 0-30 cm soil layer and the optima was also determined. Since the relationship was better for the amounts in the 0-60 cm soil layer ($r^2 = 0.22$) than for those in the 0-30 cm layer ($r^2 = 0.17$), it was decided that soil mineral nitrogen should be determined in samples from the 0-60 cm layer. The regression line in Fig. 3 was then considered to represent the recommendation. For potatoes on sandy soils and other arable crops the same procedure was followed (e.g. Bakker et al. (1981) for sugar beet). All current recommendations

Table 1. Current Dutch nitrogen fertilizer recommendations for arable crops (Anon., 1986). N_{rec} = recommended application rate of fertilizer nitrogen (kg N per ha); N_{min} = amount of soil mineral nitrogen at the end of winter (kg N per ha). For cereals the recommendation refers to the first dressing only.

Crop	Recommendation: $N_{rec} = A - B\,N_{min}$		Sampling depth for the determination of N_{min} (cm)
	A	B	
Winter wheat	140	1.0	0-100
Winter barley	120	1.0	0-100
Spring wheat	120	1.0	0-60
Oats	100	1.0	0-60
Rye	100	1.0	0-60
Sugar beet	220	1.7	0-60
Ware potatoes			
clay and loam soils	285	1.1	0-60
sandy soils	300	1.8	0-30
Industrial potatoes	275	1.8	0-30

for arable crops are summarized in Table 1. After this so-called N_{min}-method had been initiated in the Netherlands, in the Federal Republic of Germany (Wehrmann & Scharpf, 1979), Belgium (Boon, 1981), Denmark (Østergaard, 1982), and Sweden (Lindén, 1985) research was done as well to evaluate and further develop the method. It has now been adopted in these countries.

The current nitrogen fertilizer recommendations for arable crops do not appear to be based on a sound statistical basis. Since the optima were derived from hand-drawn curves, no judgment on their reliability can be made. Furthermore, there has not been a thorough statistical analysis of the factors which affect yield response to fertilizer nitrogen. Sofar, the analysis has been restricted to the linear relationship between soil mineral nitrogen at the end of winter and the optimum fertilizer nitrogen application rate. The current recommendations refer to a fixed ratio of the cost of fertilizer nitrogen to the price of crop produce, but it is unknown how the recommendations should be adjusted to a change in this ratio. It is quite well possible that the current low cost of fertilizer nitrogen will rise, not only due to higher energy costs, but possibly also due to a levy imposed on fertilizers. Another drawback of the current recommendations is that they aim only at obtaining high yields of good quality, but do not explicitly consider environmental side effects. For inclusion of environmental effects, a completely different approach is needed in which the many simultaneously occurring processes (Fig. 1) are taken into account. Dynamic simulation is an appropriate tool to describe these processes and their interactions.

In the following chapters the above-mentioned issues are examined. In Chapter 2, response curves for sugar beet and potatoes are described by mathematical functions, which allow accurate calculation of the economically optimum application rates of fertilizer nitrogen, and the reliability of the optima. In Chapter 3 a statistical analysis is performed to investigate if, and to what extent, the response of sugar beet and potatoes to fertilizer nitrogen depends on the amount of mineral nitrogen already present in the soil, the soil type, and prior application of organic manures. In Chapter 4 the performance of nitrogen fertilizer recommendations made on the basis of the results obtained in Chapter 3 is compared with the performance of the currently used recommendations. In Chapter 5 is it investigated how far fertilizer nitrogen application rates can be reduced before serious yield deficits occur, and to what extent reductions result in higher recoveries of fertilizer nitrogen. In the same chapter the effect of a change in the ratio of the cost of fertilizer nitrogen to the price of crop produce on the optimum application rate of fertilizer nitrogen is examined. In Chapter 6 a dynamic simulation model is presented to describe the response of potatoes to nitrogen and it is investigated if the model can be used to predict yield and optimum fertilizer nitrogen application rate for potatoes. Finally, in Chapter 7 the model presented in Chapter 6 is used to indicate environmental aspects of applying fertilizer nitrogen to potatoes.

The research mentioned in Chapters 2-5 was carried out with sugar beet and potatoes, because results of numerous fertilizer nitrogen trials were available. It should be noted here that potatoes and sugar beet are generally the most important crops for Dutch farmers, because these crops have a strong impact on farm income. When sugar beet and potatoes are grown in a four-year rotation with winter wheat and spring barley, they contribute up to 65 % of the total net monetary yield (Anon., 1988). The investigations mentioned in Chapters 6 and 7 were carried out with potatoes only, because at the start of the research described in this thesis many efforts had already been made to develop a simulation model for potatoes (Greenwood et al., 1985).

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Chapter 2

Assessment of economically optimum application rates of fertilizer N on the basis of response curves

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Assessment of economically optimum application rates of fertilizer N on the basis of response curves

J.J. NEETESON & W.P. WADMAN
Institute for Soil Fertility, P.O. Box 30003, 9750 RA Haren (Gn), The Netherlands

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Key words: fertilizer recommendation, N fertilizer, N-response curves, optimum N application, potato, sugar beet

Abstract. N-response curves of numerous N-fertilizer trials with sugar beet and potato are described by a quadratic and a modified exponential equation. For both sugar beet and potato the modified exponential equation was much better than the quadratic equation when the residual sum of squares (RSS) was taken as a measure of the degree of fit. In order to take into account the few occasions when the quadratic model was superior, it is suggested that both models should be used for the data of each individual trial. The economically optimum application rate of fertilizer N is calculated on the basis of the best-fitting model. This procedure yielded optima which covered entire ranges of fertilizer-N levels tested: 0–250 kg ha^{-1} for sugar beet and 0–400 kg ha^{-1} for potato. The magnitude of the confidence intervals ($p > 95\%$) of the optimum N-fertilizer application rate frequently was very high. In 46% of the sugar beet trials and even in 60% of the potato trials it was higher than 300 kg ha^{-1} N. It is suggested that N-fertilizer recommendations be drawn up only with reliable optima.

Introduction

Fertilizer recommendations are usually based on results of field trials in which crop response to various rates of fertilizer application is determined. The response curve then provides for each trial the relationship between amount of fertilizer and crop yield. From this curve the economically optimum application rate of fertilizer, i.e. the minimum amount of fertilizer N needed for maximum financial yield, can be derived. Next, fertilizer recommendations can be made by correlating the optimum application rates of fertilizer in the various trials with one or more field characteristics, for instance the amount of nutrient which is already present in the soil and available to the crop, e.g. [33].

In the Netherlands numerous N-fertilizer trials have been conducted to establish the relationship between soil characteristics and the optimum application rate of N fertilizer in order to draw up N-fertilizer recommendations for sugar beet and potato. Although it was never stated explicitly, interpretations of the experimental results were based on hand-drawn curves [20, 26], as were the recommendations [4, 22]. In drawing curves by hand it was attempted to minimize the deviations of the points from the curve. An important prerequisite for this method of curve fitting was that the drawn curve should be in agreement with the general view on the shape of response curves. Details about the method are given by Visser [34, 35]. It is obvious that this method of curve fitting is rather subjective and time consuming. In the present paper results of the fertilizer trials are re-evaluated by determining the response curves on the basis of mathematical functions. Calculation of the curves is not only objective and rapid, but also makes it possible to assess more accurately the optimum application rate of fertilizer N and to state the reliability of the calculated optima.

Materials and methods

Experimental design

In cooperation with the Sugar Research Institute (IRS, Bergen op Zoom) and the Research Station for Arable Farming and Field Production of Vegetables (PAGV, Lelystad) 167 field trials with sugar beet (*Beta vulgaris* L.) and 99 field trials with potato (*Solanum tuberosum* L.) were conducted in the period 1973–1982 (Table 1). The trials were laid out scattered over the Netherlands.

The trials with sugar beet consisted of 24 plots: six application rates of fertilizer N (0, 40, 80, 120, 160, and 200 kg ha^{-1} or 0, 50, 100, 150, 200, and 250 kg ha^{-1}) in four replications. The trials with potato consisted of 21 plots: seven application rates of fertilizer N (0, 100, 150, 200, 250, 300, and 400 kg ha^{-1}) in three replications. With few exceptions plot size was $6 \times 25 = 150\,m^2$ for sugar beet and $6 \times 9 = 54\,m^2$ for potato. The fertilizer N was applied by hand as ammonium nitrate limestone as a single dressing in March or April. On some sugar beet trials the treatments 200 and 250 kg ha^{-1} were split into two application rates of fertilizer N: 150 + 50 and 150 + 100 kg ha^{-1}. After soil analysis each experimental field was uniformly fertilized with phosphate and potassium according to the recommendations. Weed-, disease- and pest-control measures were carried out by the farmer according to his normal practice. The cultivars mostly used were Monohil for sugar beet and Bintje for potato. Fresh root yield and sugar content of the roots were determined for each sugar beet plot, and fresh tuber yield was determined for each potato plot.

Table 1. Distribution of the trials over the years. Numbers are trial numbers.

Year	Sugar beet	Potato
1973		1– 5
1974	1– 8	6– 9
1975	9– 18	10–13
1976	19– 29	14–20
1977	30– 76	21–26
1978	77–120	27–33
1979	121–167	34–39
1980		40–65
1981		66–90
1982		91–99

Determination of optimum application rate of fertilizer N

In the Netherlands the price the farmer gets for his sugar beet depends not only on root yield, but also on sugar content of the roots. The price is based on roots with a sugar content of 16%. When the roots have a lower or a higher sugar content the price will be lower or higher, respectively. This means that the relationship between root yield and price may not be linear. Linearity is a prerequisite for calculating the economically optimum application rate of fertilizer N at various prices for the crop. The monetary ratio of fertilizer cost to crop value then can be varied simply by changing the slope of the line reflecting the cost of fertilizer [5]. When the relationship between crop yield and price is not linear the economically optimum application rate of fertilizer can only be assessed by determining response curves for financial yield at each crop price. In the present study linearity between root yield and price was introduced by adjusting data on root yields in such a way that they all pertain to roots with a sugar content of 16%. In doing so it was assumed that the adjustment per percent sugar deviating from 16% amounted to 8.5% of the price per tonne roots with a sugar content of 16%, as this was approximately the average value since 1980 [19]. So the measured root yield data (RY; in $t\,ha^{-1}$) were converted into adjusted roots yields (ARY; in $t\,ha^{-1}$) taking the measured sugar content (SC; in %) into account according to equation (1):

$$\mathrm{ARY} = \mathrm{RY} + \mathrm{RY}*(\mathrm{SC} - 16) \times 0.085. \tag{1}$$

For potato an adjustment of tuber yield was not necessary, as the price the farmer gets for his ware potatoes is linearly related to tuber yield.

Nitrogen response curves are described by a quadratic or an exponential function.

The quadratic function has the form of

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

where y is yield in $t\,ha^{-1}$, N is applied fertilizer N in $kg\,ha^{-1}$ and β_0, β_1, and β_2 are coefficients which are estimated from the experimental data. The expected quadratic response curve is described by

$$\hat{y} = b_0 + b_1 N + b_2 N^2 \tag{3}$$

where $\hat{y}$ is the expected yield and b_0, b_1, and b_2 are unbiased estimations of β_0, β_1, and β_2. The coefficients b_0, b_1, and b_2 are calculated by linear regression analysis.

The optimum of the expected quadratic response curve is reached when

$$\frac{\partial \hat{y}}{\partial N} = b_1 + 2b_2 N = P \tag{4}$$

where P equals ratio of the cost of 1 kg fertilizer to the price of 1 tonne crop yield. This means that the economically optimum application rate of fertilizer

N, N_{op}, in kg ha^{-1}, is

$$N_{op} = \frac{P - b_1}{2b_2}. \tag{5}$$

The exponential function is modified by the addition of a linear term to allow for decreasing yields at nitrogen levels in excess of the level for maximum yield. The function has the form of

$$y = \beta_0 + \beta_1 N + \beta_2 e^{aN} \tag{6}$$

and the expected modified exponential response curve is described by

$$\hat{y} = b_0 + b_1 N + b_2 e^{aN}. \tag{7}$$

The meaning of y, $\hat{y}$, N, β_0, β_1, β_2, b_0, b_1, and b_2 corresponds to that in equation (2) and equation (3) and a is a constant which was predetermined to avoid non-linear regression analysis. The constant a was set equal to one of nine predetermined values defined arbitrarily by

$$a = 4 \times \ln(c)/N_{max} \tag{8}$$

where c has values of 0.03, 0.05, 0.10, 0.20, 0.35, 0.60, 0.90, 1.50, and 2.70 and N_{max} is the highest level of fertilizer N applied in kg ha^{-1}. The constant a is expressed in units of N_{max} (equation 8) to be able to apply equation (7) to both sugar beet and potato (and various other crops) with different levels of fertilizer N. The values of c cover a wide range of values of a. For each value of a the expected response curve was calculated. The response curve which yielded the lowest residual sum of squares (RSS) was considered to be the curve of best fit. In doing so one degree of freedom was taken into account. From equation (7) it can be deduced that the economically optimum application rate of fertilizer N, N_{op}, is

$$N_{op} = \frac{\ln \dfrac{P - b_1}{ab_2}}{a} \tag{9}$$

where P has the same meaning as in equation (4).

In the Appendix the deduction of the confidence limits ($p > 95\%$) of the economically optimum application rate of fertilizer N is described.

Results

Optimum application rate of fertilizer N

For each of the 167 sugar beet and the 99 potato trials the optimum application rate of fertilizer N was calculated both on the basis of the quadratic and the modified exponential response curve. The monetary ratio of fertilizer cost to crop value was fixed at 0.0125 for sugar beet and at 0.0075 for potato (a monetary ratio of 0.0075 for potato means for instance that the cost of 1 kg fertilizer N is DFL 1.50 and the price of 1 tonne tubers is Dfl. 200.00). These values are currently valid in the Netherlands [24].

When the quadratic response curve was used, the optima of 23 sugar beet and 13 potato trials fell outside the range of tested levels of fertilizer N. When the modified exponential response curve was used this phenomenon occurred in 34 sugar beet trials and 23 potato trials. These trials were omitted when the optima were compared because the optima were derived after extrapolation, which may considerably decrease reliability.

Figure 1, which gives frequency distributions of the calculated optima, shows rather large differences among optima calculated on the basis of quadratic and modified exponential response curves. The modified exponential response curve led to a higher proportion of optima at low fertilizer-N levels and to a more uniform distribution of the optima over the range of fertilizer-N levels tested. The modified exponential curve may have its optimum at low fertilizer-N levels, whereas the quadratic curve must be symmetrical around its maximum, which may lead to higher optima (Fig. 2).

To determine which of the two models was the most suitable, the residual sum of squares (RSS) of each curve was taken as a measure of best fit. For both sugar beet and potato the average RSS was lower in the modified exponential model than in the quadratic model (Table 2). In 95% of the sugar beet trials and 92% of the potato trials RSS was lower in the modified exponential model. These results show that with few exceptions the modified exponential model fitted the data best. Figure 3 shows the frequency distributions of the optima as determined with the curve of best fit, either the quadratic one or the modified

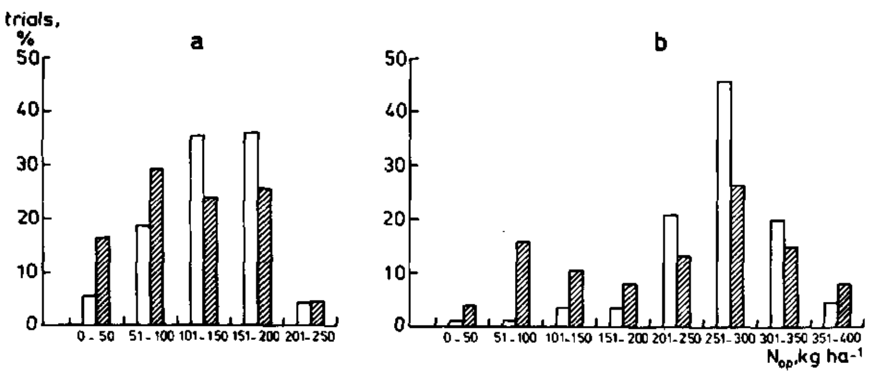

Fig. 1. Optimum application rate of fertilizer N (N_{op}) for sugar beet (a) and potato (b). N_{op} was determined on the basis of the quadratic response curve (white bars) and on the basis of the modified exponential response curve (dashed bars).

(a) Sugar beet. Number of trials: quadratic response curve = 144, modified exponential response curve = 133; monetary ratio = 0.0125.

(b) Potato. Number of trials: quadratic response curve = 86, modified exponential response curve 76; monetary ratio = 0.0075.

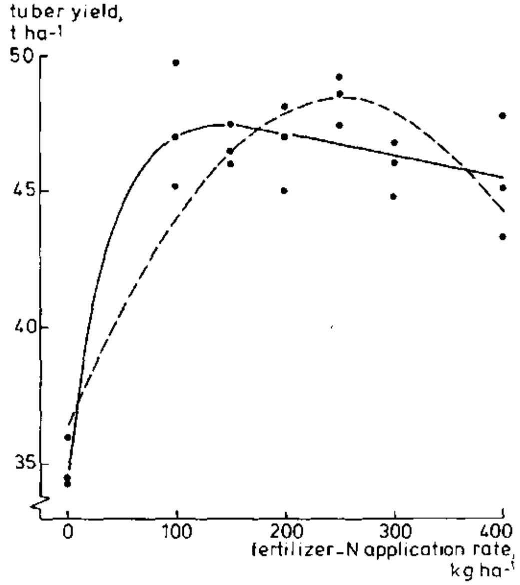

Fig. 2. Example of N-response curves for potato. Trial 60.
--- = quadratic response curve; — = modified exponential response curve.

Table 2. Average residual sum of squares (RSS) after fitting the quadratic and the modified exponential model. Sugar beet: 167 trials. Potato: 99 trials.

Model	Average RSS ($t^2\,ha^{-2}$)	
	Sugar beet	Potato
Quadratic	358	206
Modified exponential	339	191

exponential one. As in most trials the modified exponential curve is the best fitting, it is obvious that the frequency distributions in Fig. 3 very much resemble those of the modified exponential curve in Fig. 1.

Confidence intervals ($p > 95\%$) of optimum application rate of fertilizer N

For each calculated optimum application rate of fertilizer N the confidence interval was determined to distinguish between the degrees of reliability of the optima obtained.

Figure 4 shows the frequency distribution of the magnitude of the confidence intervals associated with the optima taken from Fig. 3. The optimum application rate of fertilizer N for sugar beet generally had a much narrower confidence interval than that for potato. For instance, 39% of the sugar beet trials had a

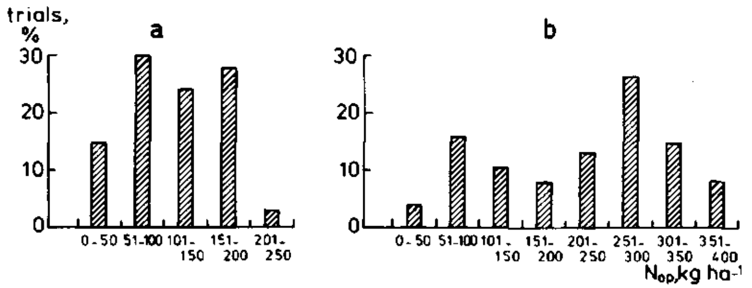

Fig. 3. Optimum application rate of fertilizer N (N_{op}) for sugar beet (a) and potato (b). N_{op} at each trial was determined on the basis of the best fitting response curve: quadratic or modified exponential. Sugar beet: 133 trials; monetary ratio = 0.0125. Potato: 76 trials; monetary ratio = 0.0075.

confidence interval of less than 100 kg ha^{-1}, whereas this was the case in only 26% of the potato trials. Apparently, the sugar beet trials yielded much more reliable results. It is striking that the confidence interval for the optimum application rate of fertilizer N was often more than 300 kg ha^{-1}. This occurred in 46% of the sugar beet trials and in 60% of the potato trials (Fig. 4). Obviously these optima cannot be used for developing fertilizer recommendations.

The absolute values of the confidence intervals of all sugar beet and potato trials, including those which were omitted in Fig. 1, are shown in Figs 5 and 6. In these figures only those parts of the confidence intervals are shown which lay within the relevant range of applied fertilizer N, viz., 0–250 kg ha^{-1} for sugar beet and 0–400 kg ha^{-1} for potato. Where no confidence interval is indicated the

Fig. 4. Magnitude of confidence interval for optimum application rate of fertilizer N (N_{op}) for sugar beet (white bars) and potato (dashed bars). N_{op} at each trial was determined on the basis of the best fitting response curve: quadratic or modified exponential. Sugar beet: 133 trails; monetary ratio = 0.0125. Potato: 76 trials; monetary ratio = 0.0075.

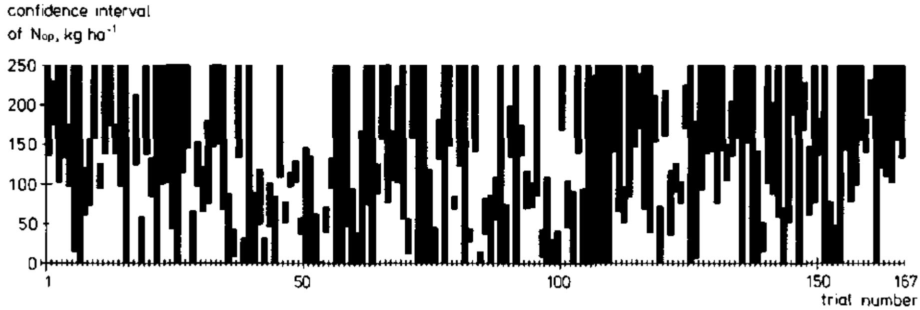

Fig. 5. Confidence interval (black bars) for optimum application rate of fertilizer N (N_{op}) for sugar beet. See Table 1 for trial numbers. Only those parts of the confidence intervals are shown which lay within the relevant range of applied fertilizer N: 0–250 kg ha^{-1}. N_{op} at each trial was determined on the basis of the best fitting response curve: quadratic or modified exponential. Number of trials = 167; monetary ratio = 0.0125.

confidence interval lay completely outside the range of the fertilizer-N levels tested. Figures 5 and 6 show that within the range of fertilizer-N levels tested the confidence intervals of the optima were also generally wide.

Discussion

Crop response to fertilizer N can be described by polynomials, inverse polynomials, exponentials, and split lines [38]. Comparison of a variety of models to response of cereals to fertilizer N showed that the model of two straight lines performed best [7, 30]. However, in the present study, which aims at describing responses of sugar beet and potato to N fertilizer, this model has not been used. The sharp break in the slope does not permit determination of the dependence of optimum N-fertilizer application rate on the monetary ratio of fertilizer cost to crop value. The model also requires many coefficients and there is an element of subjectivity in assessing the values. Moreover, the model does not appear to provide a sound basis for biological interpretation [10]. In the present paper responses of sugar beet and potato to N fertilizer are described by means of a quadratic and a modified exponential equation. The quadratic model was chosen because it has been widely used for various crops [1, 2, 13, 14, 16, 18, 23, 25, 27, 28, 29]. The modified exponential model was chosen because it was preferred to various other models in recent wheat research [10]. This was done because the model could describe the general form of N-response curves very well and required little computing time. To avoid non-linear regression analysis, which needs much computing time, George [10] and Sylvester-Bradley et al. [31] assumed a fixed value for the exponential coefficient of the modified exponential equation. In the present paper, however, the exponential coefficient first was fixed at several values to get more flexibility in the shape of the curve. Next the value which yielded the lowest residual sum of squares (RSS) was considered to be the best.

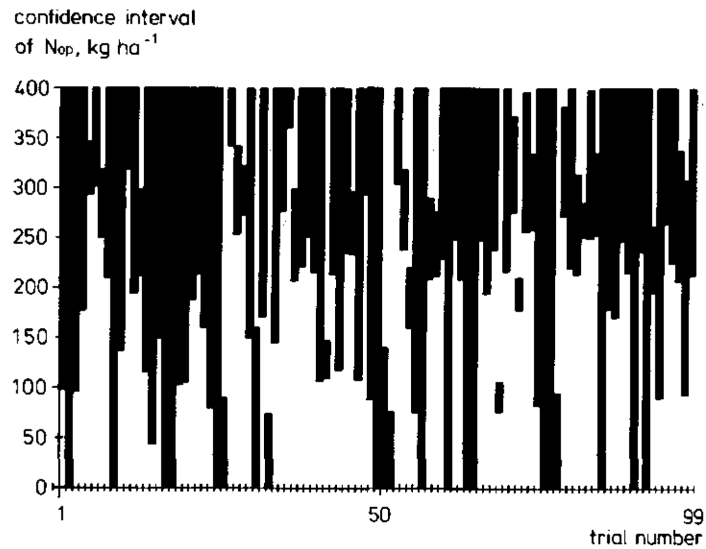

Fig. 6. Confidence interval (black bars) for optimum application rate of fertilizer N (N_{op}) for potato. See Table 1 for trial numbers. Only those parts of the confidence intervals are indicated which lay within the relevant range of applied fertilizer N: 0–400 kg ha^{-1}. N_{op} at each trial was determined on the basis of the best fitting response curve: quadratic or modified exponential. Number of trials = 99; monetary ratio = 0.0075.

Optimum application rate of fertilizer N

Use of quadratic or modified exponential N-response curves for sugar beet and potato resulted in rather large differences in the calculated optimum application rates of fertilizer N (Fig. 1). The optima were generally higher in the quadratic model. When the residual sum of squares, after fitting the models, was taken as a measure of best fit, the modified exponential model performed much better than the quadratic model (previous section on optimum application rate of fertilizer N). A disadvantage of the quadratic model is that the curve must be symmetrical around its maximum. This may lead to over-estimation of the maximum yield and under-estimation of yields at low and high fertilizer-N levels (Fig. 2). Obviously the modified exponential curve is more flexible in fitting the data points and thus gives better results. This conclusion agrees with results of Boyd et al. [7] and Sparrow [30].

A point that deserves attention is that the optimum application rate of fertilizer N for sugar beet was seldom higher than 200 kg ha^{-1}, whereas for potato it was usually higher than 200 kg ha^{-1} (Fig. 3). The N uptake by both crops, however, is more or less the same: 200–300 kg ha^{-1} [3, 9, 11, 12, 15, 17]. This apparent contrast may be explained by the ability of sugar beet to exploit the soil more effectively, probably due to a better root system [32]. Moreover, the growth period of sugar beet is about two months longer, which allows the crop to take up more soil nitrogen.

Reliability of optimum application rate of fertilizer N

In Western Europe N-fertilizer recommendations for arable crops are usually based on the relationship between soil mineral N and the optimum application rate of N fertilizer [4, 6, 8, 21, 22, 26, 36, 37]. It is striking in these papers that no attention was paid to the reliability of the optimum N application rates used for establishing the recommendations. The implication is that the recommendations were established with reliable and less reliable data which were counted equally. Confidence limits for optimum N application rates for sugar beet and potato, respectively, were calculated in the present study. Figures 4–6 show that the confidence intervals can frequently be very wide, especially for potato. The magnitude of the confidence interval depends on the variability between yields per replicate and on the shape of the curve, i.e. the significance of the coefficients b_1 and b_2 in equations (3) and (7). Confidence intervals for optimum N application rates are wide when differences among replications are large and/or the curves are flat and do not decline significantly beyond their maximum. Variability among replications depends on the homogeneity of the experimental field. Flat curves may occur when levels of soil mineral N are high before fertilizer is applied [26]. Incidence of diseases may also lead to flat curves, as shown by Dilz et al. [8]; crops not protected from diseases needed less fertilizer N. Extreme weather conditions, e.g. drought in the early stages of growth (esp. in potato) as well as heavy rainfall after fertilizer application may also decrease crop response to N fertilizer. An important reason why potato has a higher proportion of (very) wide confidence intervals for the optimum N-fertilizer application rate than sugar beet is that the N-response curves of potato generally do not decline beyond their maximum. Applying too much fertilizer N to potato seldom had a distinctly negative effect on tuber yield. The value of b_1 in equations (3) and (7) is therefore seldom significant. The value of b_1 for sugar beet is more likely to be significant as the yield, in this case root yield adjusted to a sugar content of 16%, generally decreases when too much fertilizer N is applied due to the negative relationship between amount of fertilizer N and sugar content.

N-fertilizer recommendations

In the foregoing it is shown that the modified exponential model yielded much better results than the quadratic model. This would suggest that the quadratic model should not be used and that the modified exponential model should be preferred. However, to take account of the (few) times that the quadratic model

Table 3. Average optimum application rate of fertilizer N (N_{op}) for sugar beet and potato.

Crop	Trials	Number of trials	N_{op} (kg ha^{-1})		
			Average	Lowest	Highest
Sugar beet	All trials*	133	111	3	243
	Trials with narrow confidence interval**	63	114	34	210
Potato	All trials*	76	219	1	395
	Trials with narrow confidence interval**	25	254	87	353

* Trials in which N_{op} lay within the range of fertilizer-N levels tested.
**Trials in which N_{op} lay within the range of fertilizer-N levels tested and in which the magnitude of the confidence interval of N_{op} did not exceed 150 kg ha^{-1} N.

is superior to the modified exponential model, it is proposed that both models be used for the data of each individual trial. The optimum application rate of fertilizer N and its confidence interval are then calculated on the basis of the best-fitting model using the least RSS as the criterion. This procedure yields for each trial a calculated optimum application rate of N fertilizer (at the current monetary ratio of fertilizer cost to crop value) and a measure of its reliability. Next, N-fertilizer recommendations can be established by using the reliable optima only. Finally, the recommendations developed in this way can be tested by checking whether the recommended N-fertilizer rate for each trial lies within the confidence interval of the calculated optimum. When the checks give satisfactory results the recommendations can be passed on to the farmer.

Care should be exercised to draw up recommendations only with the use of optima having narrow confidence intervals. It is quite possible that these optima lie within a limited range and do not reflect real variation. Low optima can be underestimated, because they are usually derived from flat curves and have, therefore, wide confidence intervals. Table 3 indicates that this possibly happened to potato (compare the average value of the optimum N-application rate in all trials with that in the trials with a narrow confidence interval). Notwithstanding these underestimations the optima with narrow confidence intervals covered a broad range of fertilizer-N levels (Table 3), thus enabling the establishment of fertilizer recommendations based on reliable data.

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Appendix

Calculation of the confidence interval for the optimum application rate of fertilizer

1. The quadratic response function

The economic response μ_x is given by:

$$\mu_x = \beta_0 + (\beta_1 - P)\cdot x + \beta_2\cdot x^2 + e_r, \tag{1}$$

in which

β_i = parameter to be estimated from the experimental data,

x = fertilization,

P = price ratio of one unit of μ per unit of area to one unit of x per unit of area,

e_r = normally distributed residual error.

The expected economic response $\hat{\mu}_x$ is given by:

$$\hat{\mu}_x = b_0 + (b_1 - P)\cdot x + b_2\cdot x^2, \qquad (2)$$

in which

b_i = unbiased estimate of β_i calculated by linear regression analysis.

Consider:

$$\Phi_x \equiv \frac{\partial \mu_x}{\partial_x} = (\beta_1 - P) + 2\cdot\beta_2\cdot x \qquad (3)$$

μ_x has an extreme for $x = x_e$ if Φ_x is not significantly different from zero.
It then follows that Φ_x is normally distributed and μ_{x_e} is an extreme if:

$$-t_{n-3}^{\gamma/2}\sqrt{\mathrm{var}(\hat{\Phi}_{x_e})} \leqslant \hat{\Phi}_{x_e} \leqslant t_{n-3}^{\gamma/2}\sqrt{\mathrm{var}(\hat{\Phi}_{x_e})} \rightleftharpoons \qquad (4)$$

$$\hat{\Phi}_{x_e}^2 \leqslant [t_{n-3}^{\gamma/2}]^2\,\mathrm{var}(\hat{\Phi}_{x_e}) \qquad (5)$$

in which

$\hat{\Phi}_{x_e}$ = unbiased estimated of Φ_{x_e},

$\mathrm{var}(\hat{\Phi}_{x_e})$ = variance of $\hat{\Phi}_{x_e}$,

$t_{n-3}^{\gamma/2}$ = student-t value at confidence level $\gamma/2$ with $n - 3$ degrees of freedom,

n = number of experimental observations.

p, β, b, and C are defined as follows:

$$p \equiv (0, 1, 2\cdot x)' \qquad (6)$$

$$\beta \equiv (\beta_0, \beta_1, \beta_2)' \qquad (7)$$

$$b \equiv (b_0, b_1, b_2)' \qquad (8)$$

$$C \equiv \begin{pmatrix} c_{00} & c_{01} & c_{02} \\ c_{10} & c_{11} & c_{12} \\ c_{20} & c_{21} & c_{22} \end{pmatrix} \qquad (9)$$

in which

C = the estimated covariance matrix

and

c_{ij} = the estimated covariance of b_i and b_j.

It then follows that:

$$\hat{\Phi}_{x_e} = (\widehat{p, \beta}) = (p, b) = (b_1 - P) + 2\cdot b_2\cdot x_e \qquad (10)$$

and

$$\mathrm{var}(\hat{\Phi}_{x_e}) = \mathrm{var}((p, b)) = p'\cdot C\cdot p = c_{11} + 4\cdot x_e\cdot c_{12} + 4\cdot x_e^2\cdot c_{22} \qquad (11)$$

in which

$$\widehat{(p, \beta)} = \text{unbiased estimate of } (p, \beta).$$

Combining the equations (5), (10) and (11) yields:

$$Z(x_e) \leqslant 0 \tag{12}$$

$$Z(x) \equiv a_2 \cdot x^2 + a_1 \cdot x + a_0 \tag{13}$$

$$a_2 \equiv 4 \cdot b_2^2 - 4 \cdot \tilde{c}_{22} \tag{14}$$

$$a_1 \equiv 4 \cdot (b_1 - P) \cdot b_2 - 4 \cdot \tilde{c}_{12} \tag{15}$$

$$a_0 \equiv (b_1 - P)^2 - \tilde{c}_{11} \tag{16}$$

$$\tilde{c}_{ij} \equiv c_{ij} \cdot [t_{n-3}^{\gamma/2}]^2 \tag{17}$$

$$D \equiv a_1^2 - 4 \cdot a_2 \cdot a_0, \tag{18}$$

in which

$$D = \text{the discriminant of } Z(x) = 0.$$

In Williams (1959, p. 111) the equation

$$Z(x) = 0 \tag{19}$$

is given for calculating the limits of the confidence interval (for $P = 0$).

By evaluating the sign of $Z(x)$ a γ confidence interval of x_e can be established (equation 12). The sign of $Z(x)$ is both dominated by the sign of a_2 and that of D. If $Z(x_{min}) = 0$ and $Z(x_{max}) = 0$ and $x_{min} < x_{max}$ (this means that $D > 0$), then

$$x_{min} \leqslant x_e \leqslant x_{max} \quad \text{only when} \quad a_2 > 0 \tag{20}$$

and

$$x_e \leqslant x_{min} \quad \text{and} \quad x_e \geqslant x_{max} \quad \text{only when} \quad a_2 < 0. \tag{21}$$

Only the values of x_e belonging to β_2 values which are < 0 ($\partial^2 \mu / \partial x^2 < 0$, convex response function) are optimum x values (those fertilizer applications give a maximum financial return, i).

It should also be noted that

$$a_2 > 0 \rightleftharpoons \beta_2 \neq 0 \qquad \text{(at confidence level } \gamma\text{, ii)}$$

(cf equation 14).

From (i), (ii) and equation (20) it can be concluded that a closed interval of optimum x values is established only when β_2 is significantly < 0.

2. The modified exponential response function

The economic response is given by:

$$\mu_x = \beta_0 + (\beta_1 - P) \cdot x + \beta_2 \cdot e^{a \cdot x} + e_r \tag{22}$$

in which a is a constant and P, e_r, β_i and μ_x have the same meaning as in equation (1).

When the same procedure as for the quadratic response function is followed it can be shown that μ_x has an extreme for $x = x_e$ when:

$$E(z_e) \leqslant 0 \tag{23}$$

$$E(z) \equiv e_2 \cdot z^2 + e_1 \cdot z + e_0 \tag{24}$$

$$z \equiv a \cdot \mathrm{e}^{a \cdot x} \tag{25}$$

$$e_2 \equiv b_2^2 - \hat{c}_{22} \tag{26}$$

$$e_1 \equiv 2 \cdot (b_1 - P) \cdot b_2 - 2 \cdot \hat{c}_{12} \tag{27}$$

$$e_0 \equiv (b_1 - P)^2 - \hat{c}_{11} \tag{28}$$

$$D \equiv e_1^2 - 4 \cdot e_0 \cdot e_2 \tag{29}$$

in which

D = the discriminant of $E(z) = 0$

and $\hat{c}_{ij}$ has the same meaning as in equation (17).

By evaluating the sign of $E(z)$ a γ confidence interval of x_e can be established. Again only the values of x_e belonging to negative β_2 values are optimum x values ($\partial^2 \mu_x / \partial x^2 < 0$). Because of the transformation of x_e to z_e a closed interval of z_e could lead to an interval of x_e in which the limits are exclusive (that means that infinity is included in the interval).

A closed interval of optimum x values is established only when β_2 is significantly negative and the sign of $(P - \beta_1)$ is significantly opposite to that of a.

Ref: Williams EJ (1959) Regression analysis. New York: John Wiley.

Chapter 3

An analysis of the response of sugar beet and potatoes to fertilizer nitrogen and soil mineral nitrogen

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An analysis of the response of sugar beet and potatoes to fertilizer nitrogen and soil mineral nitrogen

J. J. NEETESON & H. J. C. ZWETSLOOT

Institute for Soil Fertility, P.O. Box 30003, NL 9750 RA Haren, Netherlands

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Abstract

A statistical analysis was performed to investigate if, and to what extent, the response of sugar beet and potatoes to fertilizer nitrogen depended on the amount of mineral nitrogen already present in the soil, soil type, and prior application of organic manures. For this purpose the results of 150 field trials with sugar beet and 98 with potatoes were used. The analysis was focussed on the within-block stratum of variation in yield, where regression models were fitted to describe the response to nitrogen. For both sugar beet and potatoes the best fit was obtained when not only fertilizer nitrogen was taken into account, but also soil mineral nitrogen, soil type, and prior application of organic manures. The response to fertilizer nitrogen was weaker as the amount of soil mineral nitrogen was larger. The optimum amount of fertilizer nitrogen plus soil mineral nitrogen required was larger on sandy soils than on loam and clay soils. The difference was about 20 kg N per ha for sugar beet and 100 kg N per ha for potatoes. When organic manures were applied prior to the aplication of fertilizer nitrogen, the optimum for both sugar beet and potatoes was 15-50 kg N per ha lower than without application of organic manures.

Keywords: fertilizer nitrogen, nitrogen fertilizer recommendation, nitrogen response curve, potatoes, soil mineral nitrogen, sugar beet

Introduction

In the Netherlands, nitrogen fertilizer recommendations for arable crops are based on numerous field trials (Ris et al., 1981). On each experimental site, soil mineral nitrogen was measured in early spring and increasing amounts of fertilizer nitrogen were applied to determine the optimum application rate from the response curve. The recommendations for sugar beet and potatoes are derived from the linear relationship between the amount of mineral nitrogen (ammonium N + nitrate N) present in the soil in early spring and the economically optimum application rate of fertilizer nitrogen (Anon., 1986). The larger the amount of soil mineral nitrogen, the lower the recommended application rate of fertilizer nitrogen.

Many trials were conducted because it was believed that the linear relationship between soil mineral nitrogen and the optimum application rate of fertilizer nitrogen could be reliably established only on the basis of a large number of data points. The relationship was indeed found to be significant, but the variation around the regression line was considerable, e.g. r^2 = 0.30 with 148 sugar-beet trials and r^2 = 0.25 with 83 potato trials (Neeteson, 1982). The wide variation prevented a clear differentiation between soil types and/or fields with or without prior application of organic manures.

Neeteson & Wadman (1987) have shown that the economically optimum application rate of fertilizer nitrogen for sugar beet and potatoes, derived from response curves of individual trials, generally has a large error. It is likely that the considerable variation around regression lines of the relationship between soil mineral nitrogen and the optimum application rate of fertilizer nitrogen is partly due to the large error in the determination of the optima.

To develop a basis for refinement of the current recommendations, a statistical analysis was performed to investigate whether the response of sugar beet and potatoes was not only dependent on the amount of mineral nitrogen already present in the soil, but also on soil type and prior application of organic manures. For this purpose the results of 150 field trials with sugar beet and 98 with potatoes were used. The analysis was focussed on the within-block stratum of variation in yield, where regression models were fitted to describe the response to nitrogen.

Materials and methods

Experimental design

In cooperation with the Sugar Beet Research Institute (IRS, Bergen op Zoom) and the Research Station for Arable Farming and Field Production of Vegetables (PAGV, Lelystad), 150 field trials with sugar beet (*Beta vulgaris* L. cv. Monohil) and 98 field trials with potatoes (*Solanum tuberosum* L. cv. Bintje) were conducted in the period 1973-1982. There were altogether 167 sugar beet and 99 potato trials (Neeteson & Wadman, 1987), but trials with incomplete data on soil mineral nitrogen were omitted. Moreover, some sugar-beet trials were excluded because of unrealistically high levels of soil mineral nitrogen in early spring (>300 kg N per ha in the 0-100 cm layer). The trials were laid out in all parts of the Netherlands. The distribution of the trials over years and soil types is given in Table 1. The soils were classified on the basis of the particle-size distribution in the plough layer (Steur & Heijink, 1987). In 63 of the sugar beet and 50 of the potato trials, organic manures were applied in autumn or early winter preceding sugar beet or potato culture. The organic manures were green manures (mostly Italian ryegrass (*Lolium multiflorum* Lamk.) or vetch (*Vicia sativa* L.) and/or slurries (cattle, pig or poultry slurry; about 50 t ha^{-1}). Table 2 shows the distribution over soil types of the trials with application of organic manures.

In the sugar-beet trials, soil mineral nitrogen content was measured in early spring in samples from the layers 0-30, 30-60, and 60-100 cm, whereas in the potato trials the layers 0-30 and 30-60 cm were sampled. For each soil sample approximately 12 cores were mixed. Nitrate and ammonium were extracted with 1 M NaCl

Table 1. Distribution of the trials over years and soil types.

Year	Sugar beet				Potatoes			
	sand	loam	clay	total	sand	loam	clay	total
1973	0	0	0	0	1	3	1	5
1974	1	6	0	7	1	3	0	4
1975	3	3	2	8	1	3	0	4
1976	3	5	2	10	2	4	1	7
1977	12	20	10	42	1	4	1	6
1978	9	16	15	40	1	5	1	7
1979	8	22	13	43	1	4	1	6
1980	0	0	0	0	5	13	7	25
1981	0	0	0	0	8	11	6	25
1982	0	0	0	0	4	5	0	9
Total	36	72	42	150	25	55	18	98

Table 2. Distribution over soil types of the trials with application of organic manures.

Type(s) of organic manure	Sugar beet				Potatoes			
	sand	loam	clay	total	sand	loam	clay	total
Green manures	2	26	18	46	2	15	7	24
Slurries	10	2	1	13	8	7	1	16
Green manures + slurries	2	1	1	4	1	5	4	10
Total	14	29	20	63	11	27	12	50

and determined colorimetrically with a Technicon Autoanalyser (Ris et al., 1981). For conversion of the measured soil mineral nitrogen contents from mg per kg soil to kg ha^{-1}, the bulk density of each soil layer was measured in each experimental field in four replications. Six rates of fertilizer nitrogen ranging from 0 to 200 or 250 kg ha^{-1} were applied in four replications in the sugar-beet trials. In the potato trials, seven rates ranging from 0 to 400 kg ha^{-1} were applied in three replications. At harvest, fresh yield and sugar content of the beets were determined for each sugar-beet plot, and fresh tuber yield was determined for each potato plot. The nitrogen contents of the potato tubers were determined in the fresh material according to the Kjeldahl-method.

Statistical analysis

When results of field trials performed in different years and at different sites are analysed together, several strata of variation have to be dealt with. Usually the variation between experiments is large and the within-experiment variation differs between experiments. The following statistical model was used to describe the strata of variation and the yield response to nitrogen:

$$\underline{Y}_{klm} = \mu + \underline{T}_k + \underline{B}_{kl} + f(N) + \underline{e}_{klm} \tag{1}$$

where $\underline{Y}_{klm}$ is the yield of a plot and μ is the overall mean yield in t ha^{-1}. Subscripts k, l, and m refer to trial (k = 1. . . . , 150 (for sugar beet) or 98 (for potatoes)), block (l = 1, ... , 4 (for sugar beet) or 3 (for potatoes)), and plot (m = 1, ... , 6 (for sugar beet) or 7 (for potatoes)), respectively. $\underline{T}_k$ describes the stratum of variation between trials ($\Sigma\ \underline{T}_k = 0$), and $\underline{B}_{kl}$ the variation due to blocks within trials ($\Sigma\ \underline{B}_{kl} = 0$). The variation within the blocks is described by f(N), the function which describes yield response to nitrogen; the term $\underline{e}_{klm}$ represents the vector of residuals. This vector is normally distributed ($\underline{e}_{klm}$ = N $(0, \sigma^2)$). No attempt was made to account for the wide variation between experiments, which is due to differences in weather conditions, soils, and crop management practices. The vectors $\underline{T}_k$ and $\underline{B}_{kl}$ were estimated from the data before further analysis was performed. The analysis was focussed on the within-block stratum of variation, where regression models were fitted. To correct for the non-homogeneity of variances, the regression was weighted with the inverse of the square root of the residual variance within each individual experiment.

For sugar beet, yield response to nitrogen was described by a modified exponential curve (Neeteson & Wadman, 1987):

$$f(N) = \beta_0 + \beta_1 e^{\alpha N} + \beta_2 N; \qquad \beta_0 > 0; \beta_1, \beta_2, \text{and } \alpha < 0 \tag{2}$$

where f(N) describes fresh beet yield with a sugar content of 16 % (t ha^{-1}) and N is the amount of nitrogen (kg ha^{-1}). β_0, β_1, β_2, and α are coefficients which are estimated by non-linear regression analysis. The linear term β_2N is included in the equation to allow for decreasing yields at nitrogen rates beyond the rate for maximum yield.

For potato, β_2 was never found to be significant. Therefore, response of potato to nitrogen is described by a common exponential curve:

$$f(N) = \beta_0 + \beta_1 e^{\alpha N} \qquad \beta_0 > 0; \beta_1 \text{ and } \alpha < 0 \tag{3}$$

where f(N) describes fresh tuber yield (t ha^{-1}), and β_0, β_1, α and N have the same meaning as in Equation 2.

The economical optimum (N_{op}) of the response curves is calculated by:

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

$$N_{op} = \ln\{P/ab_1\}/a \tag{5}$$

for sugar beet and potatoes, respectively, where P equals ratio of cost of 1 kg nitrogen to the price of 1 tonne crop yield, and b_1, b_2 and a are estimated values of β_1, β_2, and α. The 90 % confidence intervals for the optima were calculated as described by Neeteson and Wadman (1987), but now also account was taken of the variance of the coefficient a.

A kind of forward selection was used to find the best-fitting model for the description of the response of sugar beet and potato to nitrogen. Firstly, the simplest model was fitted. Then, parameters were added so that the models became more complex. Sequential models were compared by means of F-tests; the variance in the denominator of the F-statistics was taken from the most complex model. As a result of the very large number of degrees of freedom, significant F-tests could be obtained with extremely complex models. However, models were not allowed to become too complex. Model selection was terminated before models were obtained which would not be applicable in practical situations.

The statistical analyses were performed with Genstat 5, Release 1.0 (Lawes Agricultural Trust, Rothamsted Experimental Station).

Results

Sugar beet

Yield response to nitrogen was fitted to various models which were based on Equation 2 (Table 3). In Model 1, yield only depends on the amount of fertilizer nitrogen applied, whereas in Models 2, 3, and 4 also soil mineral nitrogen in the various layers is accounted for. Inclusion of soil mineral nitrogen, especially the amounts in the layers 0-30 and 30-60 cm, considerably improved the goodness of fit of response to nitrogen (comparison of Model 2 with Model 1: $F = 303.2$, $P < 0.001$; comparison of Model 3 with Model 2: $F = 106.8$, $P < 0.001$). Inclusion of soil mineral nitrogen in the 60-100 cm layer further improved the goodness of fit significantly (comparison of Model 4 with Model 3: $F = 5.8$, $P < 0.001$). It should be noted here that, due to the large number of observations, even very small effects will tend to be significant. The magnitude of the effect and its practical implication are therefore far more important than its significance. The estimated values of coefficients α_1, α_2, α_3, and α_4 in Model 4 of Table 3 are −0.0143, −0.0115, −0.0122, and −0.0022 ha kg^{-1}, respectively. Apparently, the contribution of soil mineral nitrogen in the 60-100 cm layer (estimation of α_4) was only 15-19 % of that of fertilizer nitrogen or soil mineral nitrogen in the 0-30 and 30-60 cm layer (estimations of α_1, α_2, and α_3). To simplify the model, the minor contribution of soil mineral nitrogen in the 60-100 cm layer was neglected (Model 3). Still, Model 3 remains complicated and cannot be easily interpreted. To simplify the model further, the weighted contributions of fertilizer nitrogen and soil mineral nitrogen were calculated on the basis of the estimated values of α_1 (−0.0147 ha kg^{-1}), α_2 (−0.0120 ha kg^{-1}), and α_3 (−0.0147 ha kg^{-1}) in Model 3:

$$N_t = N_f + 0.82\,N_{m30} + 1.00\,N_{m60} \qquad (6)$$

where N_f is the amount of fertilizer nitrogen applied in kg ha^{-1}, and N_{m30} and N_{m60} are the amounts of soil mineral nitrogen in the 0-30 and 30-60 cm layer in kg ha^{-1}, respectively. The estimated values of β_2 were not weighted in Equation 6, because the linear part of the model has a far less pronounced effect on the optimum than

Table 3. Analysis of variance of yields in the 150 sugar beet trials.

Source of variation	Sum of squares	Degrees of freedom
Total	156470	3599
Trial stratum	117347	149
Trial × block stratum	3186	450
Trial × block × units stratum	35937	3000
Model 1: $f(N) = \beta_0 + \beta_1 e^{\alpha N_f} + \beta_2 N_f$	12115	3
Model 2: $f(N) = \beta_0 + \beta_1 e^{(\alpha_1 N_f + \alpha_2 N_{m30})} + \beta_{21} N_f + \beta_{22} N_{m30}$	15856	5
Model 3: $f(N) = \beta_0 + \beta_1 e^{(\alpha_1 N_f + \alpha_2 N_{m30} + \alpha_3 N_{m60})} + \beta_{21} N_f + \beta_{22} N_{m30} + \beta_{23} N_{m60}$	17173	7
Model 4: $f(N) = \beta_0 + \beta_1 e^{(\alpha_1 N_f + \alpha_2 N_{m30} + \alpha_3 N_{m60} + \alpha_4 N_{m100})} + \beta_{21} N_f + \beta_{22} N_{m30} + \beta_{23} N_{m60} + \beta_{24} N_{m100}$	17245	9
Model 5: $f(N) = \beta_0 + \beta_1 e^{\alpha N_t} + \beta_2 N_t$	16513	3
Model 6: $f(N) = \beta_{0j} + \beta_{1j} e^{\alpha_j N_t} + \beta_{2j} N_t$	17223	7
Model 7: $f(N) = \beta_{0ij} + \beta_{1ij} e^{\alpha_{ij} N_t} + \beta_{2ij} N_t$	17579	23
Residual of Model 7	18358	2977

See Equation 2 for meaning of f(N), $\beta_0, \beta_1, \beta_2$ and α; N_f = fertilizer-N rate in kg ha^{-1}; N_{m30} = soil mineral N in the layer 0-30 cm in kg ha^{-1}; N_{m60} = soil mineral N in the layer 30-60 cm in kg ha^{-1}; N_{m100} = soil mineral N in the layer 60-100 cm in kg ha^{-1}; $N_t = N_f + 0.82\ N_{m30} + 1.00\ N_{m60}$; i = index for soil type; j = index for application of organic manures.

the exponential part. In Models 5, 6 and 7 the amount of available nitrogen was assumed to equal N_t. Somewhat less of the variance in yield was accounted for in Model 5 than in Model 3, but the number of degrees of freedom in Model 5 was also less than half of that in Model 3. Compared with Model 5, a significantly better fit of the nitrogen response was obtained in Model 6, in which a distinction is made between fields which did and did not receive organic manures prior to the application of inorganic fertilizer nitrogen (comparison of Model 6 with Model 5: $F = 28.8$, $P < 0.001$). The best fit, however, was obtained in Model 7, in which not only the application of organic manures is taken into account, but also the soil type (comparison of Model 7 with Model 6: $F = 3.6$, $P < 0.001$).

The estimated values of the regression coefficients of Model 7 are given in Table 4. The economically optimum nitrogen requirement for the various soil types with and without application of organic manures was then calculated (Table 5). The ratio of the cost of 1 kg nitrogen (fertilizer + soil mineral nitrogen according to Equation 6) to the price of 1 tonne sugar beet, P in Equation 4 was assumed to be 0.008. Without organic manures the optimum nitrogen requirement (fertilizer + soil mineral nitrogen) on sandy soils was about 20 kg N per ha higher than that on loam and clay soils. When organic manures were applied prior to the application of fertilizer

Table 4. Response curves of sugar beet. Estimated values of the regression coefficients of Model 7 in Table 3. Standard errors are given in parentheses.

Soil type	Organic manures	b_0 ($t\ ha^{-1}$)	b_1 ($t\ ha^{-1}$)	b_2 ($t\ kg^{-1}$)	a ($ha\ kg^{-1}$)
Sand	no	70.8 (4.35)	−32.7 (3.34)	−0.022 (0.013)	−0.0129 (0.003)
	yes	67.8 (2.55)	−26.6 (4.49)	−0.024 (0.008)	−0.0178 (0.006)
Loam	no	94.3 (10.69)	−53.9 (10.03)	−0.095 (0.027)	−0.0083 (0.002)
	yes	82.8 (8.61)	−36.6 (7.61)	−0.066 (0.022)	−0.0091 (0.003)
Clay	no	78.7 (4.39)	−40.6 (3.68)	−0.051 (0.012)	−0.0115 (0.002)
	yes	69.6 (2.45)	−32.3 (2.92)	−0.031 (0.009)	−0.0196 (0.004)

Table 5. Economically optimum nitrogen requirement (fertilizer + soil mineral nitrogen according to Equation 6 of sugar beet as affected by soil type and application of organic manures. The 90 % confidence interval for the optima is given in parentheses.

Soil type	Organic manures	Optimum nitrogen requirement ($kg\ ha^{-1}$)
Sand	no	205 (192-235)
	yes	153 (136-172)
Loam	no	176 (170-183)
	yes	165 (155-171)
Clay	no	180 (172-193)
	yes	142 (134-158)

nitrogen, the optimum was 15-50 kg N per ha lower than without application of organic manures.

Potatoes

Yield response to nitrogen was fitted to various models which were based on Equation 3 (Table 6). In Model 1, yield was fitted as being dependent only on the amount of fertilizer nitrogen applied, whereas in Models 2 and 3 also soil mineral nitrogen in the various layers was taken into account. Inclusion of soil mineral nitrogen, especially the amount in the layer 0-30 cm, significantly improved the fit of response to nitrogen (comparison of Model 2 with Model 1: $F = 152.5$, $P < 0.001$; comparison of Model 3 to Model 2: $F = 19.8$, $P < 0.001$). The estimated values of coefficients α_1, α_2, and α_3 are −0.012, −0.008, and −0.004 ha kg^{-1}, respectively. The total contribution of soil mineral nitrogen and fertilizer nitrogen to the nitrogen response, N_t, can thus be described as:

$$N_t = N_f + 0.67\,N_{m30} + 0.33\,N_{m60} \qquad (7)$$

where N_f, N_{m30}, and N_{m60} have the same meaning as in Equation 6. Apparently, the

Table 6. Analysis of variance of yields in the 98 potato trials.

Source of variation	Sum of squares	Degrees of freedom
Total	82149	2057
Trial stratum	58878	97
Trial × block stratum	1459	196
Trial × block × units stratum	21812	1764
Model 1: $f(N) = \beta_0 + \beta_1 e^{\alpha N_f}$	11878	2
Model 2: $f(N) = \beta_0 + \beta_1 e^{(\alpha_1 N_f + \alpha_2 N_{m30})}$	12640	3
Model 3: $f(N) = \beta_0 + \beta_1 e^{(\alpha_1 N_f + \alpha_2 N_{m30} + \alpha_3 N_{m60})}$	12739	4
Model 4: $f(N) = \beta_0 + \beta_1 e^{\alpha N_t}$	12739	2
Model 5: $f(N) = \beta_{0j} + \beta_{1j} e^{\alpha_j N_t}$	12897	5
Model 6: $f(N) = \beta_{0ij} + \beta_{1ij} e^{\alpha_{ij} N_t}$	13082	17
Residual of Model 6	8730	1747

See Equation 3 for meaning of f(N), β_0, β_1, and α; $N_t = N_f + 0.67\ N_{m30} + 0.33\ N_{m60}$; see Table 3 for meaning of other symbols.

Table 7. Response curves of potatoes. Estimated values of the regression coefficients of Model 6 in Table 6. Standard errors are given in parentheses.

Soil type	Organic manures	b_0 ($t\ ha^{-1}$)	b_1 ($t\ ha^{-1}$)	a ($ha\ kg^{-1}$)
Sand	no	59.0 (0.76)	−19.7 (1.09)	−0.0086 (0.0013)
	yes	57.2 (0.58)	−13.2 (0.97)	−0.0084 (0.0015)
Loam	no	57.7 (0.32)	−18.9 (0.67)	−0.0119 (0.0010)
	yes	56.6 (0.25)	−17.3 (0.79)	−0.0149 (0.0015)
Clay	no	57.0 (0.90)	−14.7 (1.78)	−0.0115 (0.0036)
	yes	56.2 (0.52)	−13.4 (1.59)	−0.0117 (0.0027)

effect of soil mineral nitrogen in the 0-30 cm layer was twice as large as that of the nitrogen in the 30-60 cm layer. In Models 4, 5 and 6 the amount of available nitrogen was assumed to equal N_t. Compared with Model 4 a significantly better fit of the nitrogen response was obtained in Model 5, where a distinction is made between fields which did and did not receive organic manures prior to the application of the inorganic fertilizer nitrogen (comparison of Model 5 with Model 4: $F = 10.5$, $P < 0.001$). The best fit was obtained in Model 6, in which not only the application of organic manures is taken into account, but also the type of soil (comparison of Model 6 with Model 5: $F = 3.1$, $P < 0.001$).

Table 8. Economically optimum nitrogen requirement (fertilizer + soil mineral nitrogen according to Equation 7) of potatoes as affected by soil type and application of organic manures. The 90 % confidence interval for the optima is given in parentheses.

Soil type	Organic manures	Optimum nitrogen requirement ($kg\ ha^{-1}$)
Sand	no	410 (356-486)
	yes	370 (280-467)
Loam	no	320 (294-351)
	yes	265 (236-307)
Clay	no	306 (254-388)
	yes	295 (265-353)

Table 9. Average values of measured maximum tuber yield and amount of nitrogen in the tubers of potatoes. The standard error is given in parentheses; n = number of trials.

Soil type	Organic manures	n	Maximum tuber yield ($t\ ha^{-1}$)	N in tubers at maximum tuber yield ($kg\ ha^{-1}$)	N in tubers ($kg\ t^{-1}$)
Sand	no	14	61.4 (1.34)	244 (5.59)	3.97
	yes	11	60.9 (2.60)	231 (9.28)	3.79
Loam	no	28	53.1 (1.59)	199* (7.41)	3.75
	yes	27	57.3 (1.69)	214 (7.08)	3.73
Clay	no	6	58.4 (4.09)	226 (16.41)	3.87
	yes	12	59.4 (2.74)	231 (11.68)	3.89

* $n = 26$.

The estimated values of the regression coefficients of Model 6 are given in Table 7. The economically optimum nitrogen requirement for the various soil types with and without application of organic manures was then calculated (Table 8). In the optima of Table 8, fertilizer nitrogen and soil mineral nitrogen are both included according to Equation 7. The ratio of the cost of 1 kg nitrogen (fertilizer + soil mineral nitrogen according to Equation 7) to the price of 1 tonne potato tubers, P in Equation 5, was assumed to be 0.005. Without organic manures the optimum nitrogen requirement (fertilizer and soil mineral nitrogen) on sandy soils was about 100 kg N per ha higher than on loam and clay soils. When organic manures were applied prior to the application of fertilizer nitrogen, the optimum was 15-50 kg N per ha lower than that obtained without application of organic manures.

To help explain the differences in response to nitrogen, the measured maximum tuber yields and the corresponding amounts of nitrogen in the tubers are given in Table 9. The highest yields and nitrogen uptakes were generally obtained on the sandy soils.

Discussion

Soil mineral nitrogen

The results presented show that response of sugar beet and potatoes to nitrogen is not only dependent on the rate of fertilizer nitrogen application but also on the amount of soil mineral nitrogen present in early spring before fertilizer is applied. This finding is not new, and has been reported extensively in the literature (Greenwood, 1986). However, no differentiation has been made so far between the contribution of mineral nitrogen in the various soil layers to the nitrogen response. When more than one layer was taken into account, the contributions of soil mineral nitrogen in the different layers were given equal weight (Boon & Vanstallen, 1983; Lindén, 1987; Maidl & Fischbeck, 1986; Müller & Moritz, 1982; Stieberitz et al., 1986).

The results presented in this paper demonstrated that, for sugar beet, the contribution of soil mineral nitrogen in the 0-30 cm layer was about the same as that in the 30-60 cm layer and that it was about 80 % of the contribution of fertilizer nitrogen. The contribution of soil mineral nitrogen in the 60-100 cm layer, however, was 5-6 times smaller and was assumed to be negligible. For potatoes the contribution of soil mineral nitrogen in the 0-30 cm layer to the response to nitrogen was 67 % of that of fertilizer nitrogen, and it was 33 % for the 30-60 cm layer. The relatively larger contribution of fertilizer nitrogen in the case of potatoes compared with sugar beet is probably the result of the fact that potatoes are grown in ridges. When the ridges are made and the tubers are planted, the fertilizer, which is usually broadcast shortly before, is moved close to the tubers. The results further suggest that uptake of nitrogen by sugar beet and potatoes predominantly takes place in the 0-60 and 0-30 cm layer, respectively. It was reasoned that the differences between the two crops in uptake from these layers could be attributable to differences in root density. However, in the literature no large differences in root density between sugar beet and potatoes in the 0-30 and 30-60 cm layer could be found, but root density in the 60-90 cm layer was found to be higher for sugar beet than for potatoes (de Willigen & van Noordwijk, 1987). Downward movement of nitrate can occur in spring, and the nitrate originally present in the 30-60 cm layer is then partly leached into the 60-90 cm layer, where it is still available to sugar beet, but not to potatoes.

For potatoes, another reason for the relatively low contribution of the amount of soil mineral nitrogen in the 30-60 cm layer in Equation 7 is the high correlation between the amount of mineral nitrogen present in the 0-30 cm layer and that in the 30-60 cm layer ($r^2 = 0.83$).

Soil type

The response of potatoes to fertilizer nitrogen and soil mineral nitrogen was much higher on sandy soils than on clay and loam soils. Lauer (1986) and Müller et al. (1986) also found a stronger response of potatoes on sandy soils and attributed it to a higher susceptibility to nitrate leaching and/or a lower nitrogen mineralization rate. Heavier nitrogen losses in sandy soils through leaching in the interval between early spring and the end of the uptake period of nitrogen by the potatoes played probably a role. It is unlikely, however, that the rate of mineralization was lower in sandy soils, because in the present experiments uptake of nitrogen by the crop on plots without fertilizer nitrogen (0N plots) varied little among the soil types: calculated on the basis of the measured values of the amount of nitrogen present in the tubers and the assumption that total nitrogen uptake is 1.2 times the amount of nitrogen present in the tubers (Neeteson et al., 1987), crop uptake on the 0N plots of fields without organic manures was, on average, 139 kg ha $^{-1}$ on the sandy soils, 120 kg ha^{-1} on the loam soils, and 144 kg ha^{-1} on the clay soils.

Another reason for the stronger response of potatoes on sands could be the higher yield level obtained (Table 9). The amount of nitrogen in the tubers per unit of yield was largely independent of the maximum yield level (Table 9), and as the amount of nitrogen in the tubers is linearly related to total uptake of nitrogen (Neeteson et al., 1987), higher yields are accompanied by higher nitrogen requirements.

The response of sugar beet to fertilizer nitrogen and soil mineral nitrogen was also higher on sandy soils, although to a much lesser extent than in the case of potatoes. Draycott & Durrant (1973) and Webster et al. (1977) also found that sugar beet required more nitrogen on sandy soils than on heavier soils. Nitrogen losses as a result of the higher risk of leaching are probably responsible for the somewhat stronger response on sands. Because there are no data available on nitrogen uptake by sugar beet in the experiments described in this paper, it cannot be checked whether nitrogen mineralization rates on the sugar-beet fields were different for the different soil types. Again, it is unlikely that the soils differed in mineralization rate, because generally the same fields were used for sugar beet as well as potato production. It is unlikely either that the yield level obtained by the sugar beet on sands played a role. On the contrary, without application of organic manures the maximum yields on the heavier soils tended to be higher. They were 58.2 $\pm$ 2.69, 64.5 $\pm$ 1.24 and 62.3 $\pm$ 2.56 t ha^{-1}, on sandy, loam, and clay soils, respectively.

Organic manures

When organic manures were applied prior to the application of fertilizer nitrogen, the response of both sugar beet and potatoes to fertilizer nitrogen and soil mineral nitrogen was weaker than when no organic manures were applied. To get an estimate of the amount of nitrogen mineralized from the organic manures, the average total uptake, i.e. 1.2 times the measured amount of nitrogen in the tubers (Neeteson et al., 1987), on 0N plots on fields without organic manures was subtracted from the uptake on fields with organic manures. The extra uptake on fields with organic manures averaged 30 kg ha^{-1} on sandy soils, 43 kg ha^{-1} on loam soils, and 49 kg ha^{-1} on clay soils. These figures are in agreement with the amount expected when 50 t cattle slurry per ha is applied in autumn containing 0.44 % N and having an efficiency index of 20 % (Kolenbrander, 1981), or when ryegrass or a legume is grown as a green manure (Last et al., 1981). The extra uptake of 30-50 kg N per ha is partly the result of nitrogen which was mineralized from the organic manures during autumn and winter and which was included in the measurement of soil mineral nitrogen in early spring, and partly from the amount of nitrogen mineralized afterwards. When organic manures had been applied, the amount of soil mineral nitrogen in the 0-60 cm layer in early spring was on sandy soils on average 24, on loam soils 25, and on clay soils 52 kg N per ha larger than when no organic manures had been applied. When it is assumed that the recovery by the crop of soil mineral nitrogen in early spring was 50 % and that the nitrogen mineralized in the growing season is entirely taken up by the crop, the amount of nitrogen mineralized from the organic manures in the growing season was on average 18, 31, and 23 kg N per ha, on sandy, loam, and clay soils, respectively.

Apparently, a substantial part of the nitrogen from organic manures is mineralized in the growing season, but is not explicitly accounted for in the current nitrogen fertilizer recommendations in the Netherlands (Anon., 1986). It therefore appears to be better to take the extra amount of nitrogen mineralized from organic manures during the growing season into account in the nitrogen fertilizer recommendations, as is currently practised in the Federal Republic of Germany (Wehrmann & Scharpf, 1986).

Nitrogen fertilizer recommendations

On the basis of the results presented in Tables 5 and 8, general guidelines for the economically optimum application rate of fertilizer nitrogen for sugar beet and potatoes can be drawn up. It remains to be investigated whether these refined recommendations, which not only take soil mineral nitrogen into account, but also soil type and prior application of organic manures, are more effective than the current recommendations.

Acknowledgement

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Chapter 4

Evaluation of the performance of three advisory methods for nitrogen fertilization of sugar beet and potatoes

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Evaluation of the performance of three advisory methods for nitrogen fertilization of sugar beet and potatoes

J. J. NEETESON

Institute for Soil Fertility, P.O. Box 30003, NL 9750 RA Haren, Netherlands

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Abstract

The performances of three different nitrogen fertilizer recommendation methods were retrospectively tested with data obtained from 150 fertilizer nitrogen trials with sugar beet and 98 trials with potatoes, which were conducted in the Netherlands in the period 1973-1982. The recommendations consisted of applying a fixed fertilizer nitrogen rate in all situations (126 kg N per ha for sugar beet and 286 kg N per ha for potatoes), the current Dutch method, which takes only the amount of mineral nitrogen present in the soil in early spring into account, and a refinement of the current method, which also takes soil type and recent applications of organic manures into account. On average, significantly lower amounts of fertilizer nitrogen were recommended with the current method. The difference from the other methods was on average 25 kg N per ha for sugar beet and 30 kg N per ha for potatoes. With the refined current method the highest crop yields were obtained, but the difference from the other methods was not significant and averaged only 0.3-0.4 t ha^{-1} for sugar beet and 0.1-0.2 t ha^{-1} for potatoes. The recovery of fertilizer nitrogen by the potato tubers was 2 % higher with the current method than with the other methods. Based on these findings it is concluded that the current recommendation method is preferable to the other methods.

Keywords: crop yield, fertilizer nitrogen rate, nitrogen fertilizer recommendation, fertilizer nitrogen recovery, potatoes, sugar beet

Introduction

In the Netherlands the current nitrogen fertilizer recommendation method for sugar beet and potatoes is based on the amount of mineral nitrogen present in the soil in early spring (Anon., 1986). The larger the amount of soil mineral nitrogen, the lower the recommended application rate of fertilizer nitrogen. With two exceptions, viz. potatoes on sandy soils and sugar beet grown after green manure application, no account is taken in the recommendations of soil types and presence or absence of recently applied organic manures; these two factors have recently been shown to affect the response of sugar beet and potatoes to fertilizer nitrogen as well (Neeteson & Zwetsloot, 1989). Therefore, the current recommendation method can be refined by taking soil type and organic manures into account.

The purpose of this paper is to compare the performance of various methods of nitrogen fertilizer recommendation for sugar beet and potatoes. The method of applying a fixed rate for each crop in all situations without considering soil mineral nitrogen (Tinker, 1965; Dilz, 1981; Neeteson, 1985) is used as the reference method. The fixed-rate method is compared with the current nitrogen fertilizer recommendation method, which takes account of soil mineral nitrogen, and a method based on the results of Neeteson & Zwetsloot (1989), which, in addition to soil mineral nitrogen, takes account of soil type and prior application of organic manures. The performances of the different methods are evaluated by determining the differences in recommended rates of fertilizer nitrogen, and in yields and recovery of fertilizer nitrogen from the response curves obtained in 150 sugar beet and 98 potato trials conducted earlier.

Materials and methods

Experiments

The performances of three nitrogen fertilizer recommendation methods were compared after the various recommended rates had been retrospectively applied to 150 sugar beet and 98 potato trials. It should be noted that the recommendations were made on the basis of the same trials. Unlike others (Sylvester-Bradley et al., 1987a,b), who used one-third of the trials available for constructing the recommendations and two-thirds for testing them, the whole body of trials available was used both for constructing and testing the recommendations, so as to base the recommendations on as many data as possible.

In the trials, soil mineral nitrogen was measured in various layers in early spring, and yield was measured at six or seven levels of fertilizer nitrogen. In the potato trials, also the amount of nitrogen in the tubers at harvest was measured. Details of the experimental design are given elsewhere (Neeteson & Wadman, 1987; Neeteson & Zwetsloot, 1989). When applicable, the recommended rates were calculated on the basis of the measured values of soil mineral nitrogen. The yield obtained with each recommendation was interpolated from the response curve of each individual trial. Modified exponential response curves (for sugar beet) or simple exponential response curves (for potatoes) were fitted to the measured yields (Neeteson & Zwetsloot, 1989). For sugar beet the yields were expressed as fresh beet yields with a sugar content of 16 % (Neeteson & Wadman, 1987), and for potatoes as fresh tuber yields. The nitrogen recovery by the potato tubers was interpolated from the measured amounts of nitrogen in the tubers at the fertilizer nitrogen levels actually applied. The recovery was calculated according to the difference method, i.e. the difference between nitrogen uptake with and without fertilizer nitrogen application, expressed as a percentage of the amount of fertilizer nitrogen applied.

Nitrogen fertilizer recommendations

The recommendation methods show an increasing order of refinement: a fixed rate

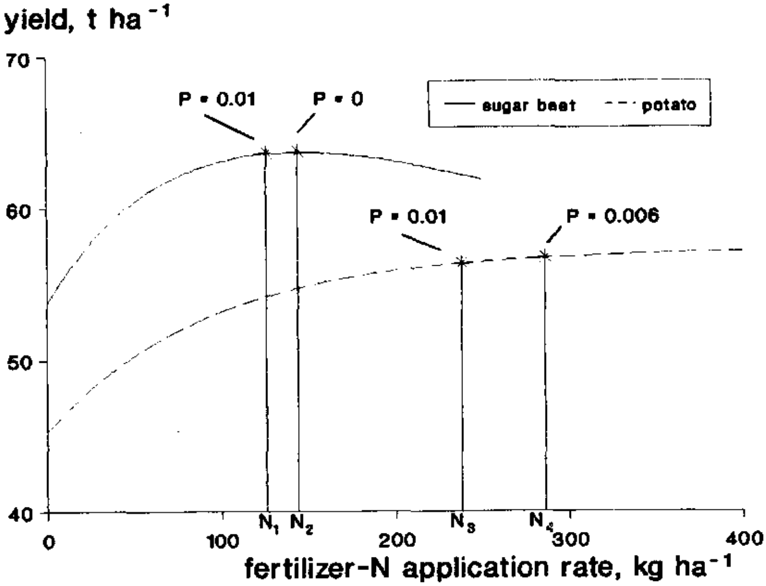

Fig. 1. Average response curves of sugar beet and potatoes. N_1 and N_2 = optimum application rate of fertilizer nitrogen for sugar beet when the monetary ratio P is 0.01 and 0, respectively. N_3 and N_4 = optimum application rate of fertilizer nitrogen for potatoes when the monetary ratio P is 0.01 and 0.006, respectively.

in all situations (REC A), the current recommendation (REC B), and the recommendation based on the results of Neeteson & Zwetsloot (1989) (REC C). The recommended rate with REC A was assumed to be the optimum fertilizer nitrogen rate as calculated from the average response curves (Fig. 1) of the 150 sugar beet and 98 potato trials which were used to test the recommendations. The ratio P of the cost of 1 kg fertilizer nitrogen to the price of 1 tonne crop yield was assumed to be 0.01 for sugar beet and 0.006 for potatoes. These values are lower than those used previously (Neeteson & Wadman, 1987) due to the current low costs of fertilizer nitrogen. The optimum rates were 126 (95 % confidence interval 121-132) kg N per ha for sugar beet and 265 (95 % confidence interval 263-302) kg N per ha for potatoes. The recommended rates with REC B were adapted from the recommendations given in Anon. (1986) in such a way that the ratio P was 0.01 for sugar beet and 0.006 for potatoes. This implied 20 kg N per ha less for sugar beet ($N_2 \rightarrow N_1$ in Fig. 1) and 50 kg N per ha more for potato ($N_3 \rightarrow N_4$ in Fig. 1), because the ratio P in the current recommendations is 0 for sugar beet (the cost of fertilizer nitrogen is not taken into account) and 0.01 for potato (Anon., 1986). The recommended rates with REC C were derived from Neeteson & Zwetsloot (1989; Tables 3 and 6). The recommendations used are shown in Tables 1 and 2.

Table 1. Nitrogen fertilizer recommendations for sugar beet. N_{rec} = recommended rate; $N_{m0\text{-}30}$, $N_{m30\text{-}60}$, and $N_{m0\text{-}60}$ are the amounts of soil mineral nitrogen in the layers 0-30, 30-60 and 0-60 cm, respectively. All amounts are expressed in kg N per ha.

Recommendation	Soil type(s)	Organic manures	N_{rec}
REC A	sand, loam, clay	no, yes	126
REC B	sand, loam, clay	no, yes[1]	$200 - 1.7\ N_{m0\text{-}60}$[2]
	sand, loam, clay	green manures	$170 - 1.7\ N_{m0\text{-}60}$[3]
REC C	sand	no	$205 - 0.8\ N_{m0\text{-}30} - N_{m30\text{-}60}$
	loam	no	$175 - 0.8\ N_{m0\text{-}30} - N_{m30\text{-}60}$
	clay	no	$180 - 0.8\ N_{m0\text{-}30} - N_{m30\text{-}60}$
	sand	yes	$155 - 0.8\ N_{m0\text{-}30} - N_{m30\text{-}60}$
	loam	yes	$165 - 0.8\ N_{m0\text{-}30} - N_{m30\text{-}60}$
	clay	yes	$140 - 0.8\ N_{m0\text{-}30} - N_{m30\text{-}60}$

[1] With the exception of green manures.
[2] When $N_{m0\text{-}60}$ is 100-150, N_{rec} is fixed at 30; when $N_{m0\text{-}60} > 150$, N_{rec} is 0.
[3] When $N_{m0\text{-}60}$ is 85-135, N_{rec} is fixed at 30; when $N_{m0\text{-}60} > 135$, N_{rec} is 0.

Table 2. Nitrogen fertilizer recommendations for potatoes. See legend of Table 1 for meaning of N_{rec}, $N_{m0\text{-}30}$, $N_{m30\text{-}60}$, and $N_{m0\text{-}60}$. All amounts are expressed in kg N per ha.

Recommendation	Soil type(s)	Organic manures	N_{rec}
REC A	sand, loam, clay	no, yes	286
REC B	sand	no, yes	$350 - 1.8\ N_{m0\text{-}30}$
	loam, clay	no, yes	$320 - 1.1\ N_{m0\text{-}60}$
REC C	sand	no	$410 - 0.7\ N_{m0\text{-}30} - 0.3\ N_{m30\text{-}60}$
	loam	no	$320 - 0.7\ N_{m0\text{-}30} - 0.3\ N_{m30\text{-}60}$
	clay	no	$305 - 0.7\ N_{m0\text{-}30} - 0.3\ N_{m30\text{-}60}$
	sand	yes	$370 - 0.7\ N_{m0\text{-}30} - 0.3\ N_{m30\text{-}60}$
	loam	yes	$265 - 0.7\ N_{m0\text{-}30} - 0.3\ N_{m30\text{-}60}$
	clay	yes	$295 - 0.7\ N_{m0\text{-}30} - 0.3\ N_{m30\text{-}60}$

Results

Recommended rates of fertilizer nitrogen

For both sugar beet and potatoes the average recommended rate of fertilizer nitrogen was significantly ($P < 0.001$) lower with the current method (REC B) than with the fixed-rate method (REC A) or the refined current method (REC C) (Table 3). The difference was approximately 25 kg N per ha for sugar beet and 30 kg N per ha for potatoes. For sugar beet, the recommended fertilizer nitrogen rates of REC B

Table 3. Recommended fertilizer nitrogen rate if various nitrogen fertilizer recommendation methods had been applied to sugar beet and potatoes. Average values of 150 sugar beet and 98 potato trials. Standard errors are given in parentheses. See Tables 1 and 2 for meaning of REC A, REC B, and REC C.

Recommendation	Recommended fertilizer nitrogen rate (kg ha^{-1})	
	sugar beet	potatoes
REC A	126 (–)	286 (–)
REC B	98 (3.77)	257 (5.07)
REC C	120 (3.13)	288 (5.48)

were about equally distributed between 25 and 175 kg N per ha, whereas the majority (75 %) of the recommended rates of REC C fell within a much narrower range, viz. between 100 and 175 kg N per ha (Fig. 2a). For potatoes the reverse was true: the recommended rates of REC C were about equally distributed between 200 and 400 kg N per ha, whereas 60 % of the rates of REC B were between 250 and 300 kg N per ha (Fig. 2b).

Yields obtained

For both sugar beet and potatoes the highest average yields were obtained with REC C, but the differences from REC A and REC B were not significant. The difference was only 0.3-0.4 t ha^{-1} for sugar beet and 0.1-0.2 t ha^{-1} for potatoes (Table 4).

In Fig. 3, frequency distributions of the yield deficits are shown, i.e. the deviations of the yield from that obtained with the measured economically optimum amount of fertilizer nitrogen in each individual trial, if the various recommended rates of fertilizer nitrogen had been applied. In the calculations, 21 sugar beet and 24 potato trials were excluded, because the measured optima fell outside the range of fertilizer nitrogen levels tested. A deficit is negative when the yield obtained with a recommendation is higher than the yield at the measured optimum amount of fertilizer nitrogen. This occurred frequently with potatoes, because with any amount of fertilizer nitrogen larger than the optimum amount, yield is higher due to the asymptotic form of the response curve used for potatoes (normal exponential

Table 4. Yields of sugar beet and potato if various nitrogen fertilizer recommendation methods had been applied. Average values of 150 sugar beet and 98 potato trials. Standard errors are given in parentheses. See Tables 1 and 2 for meaning of REC A, REC B, and REC C.

Recommendation	Yield (t ha^{-1})	
	sugar beet	potatoes
REC A	63.7 (0.86)	56.9 (0.87)
REC B	63.8 (0.89)	56.8 (0.88)
REC C	64.1 (0.86)	57.0 (0.88)

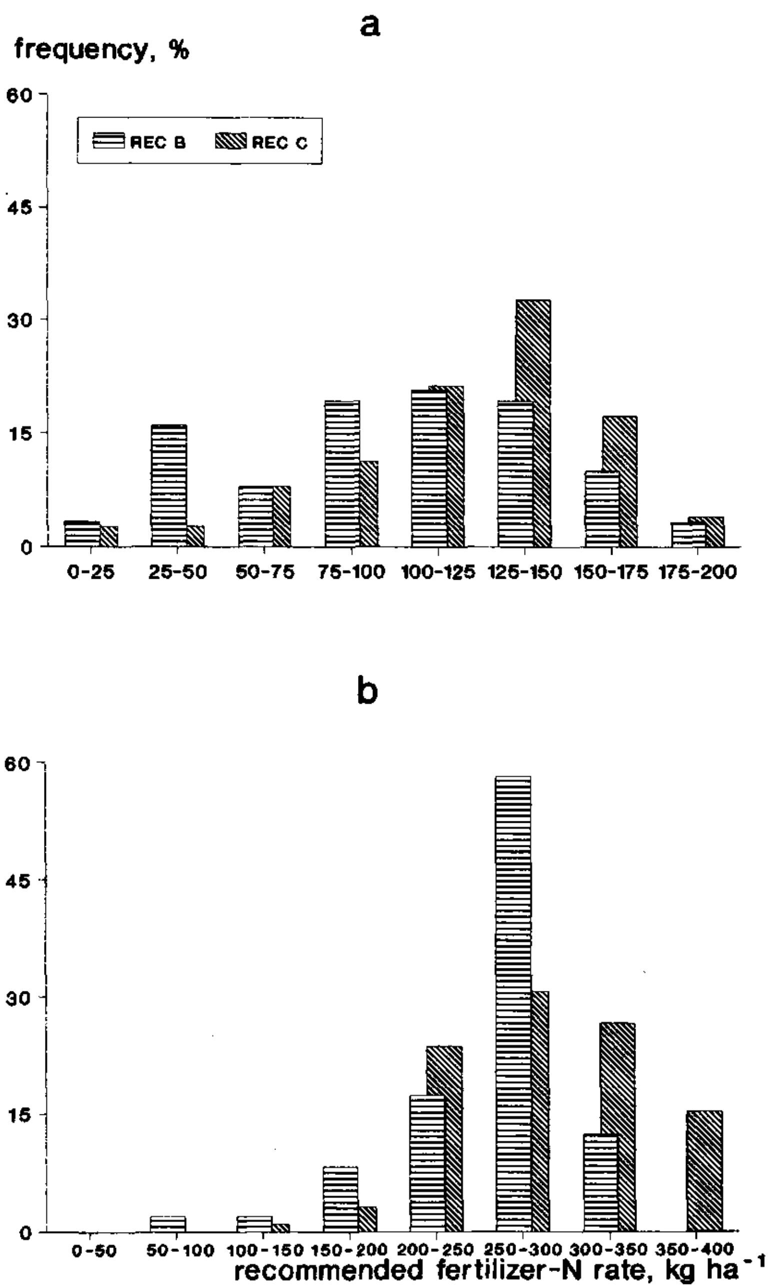

Fig. 2. Frequency distribution of the recommended fertilizer nitrogen rates for sugar beet (a) and potatoes (b) if REC B and REC C had been applied to 150 sugar beet and 98 potato trials. See Tables 1 and 2 for REC B and REC C.

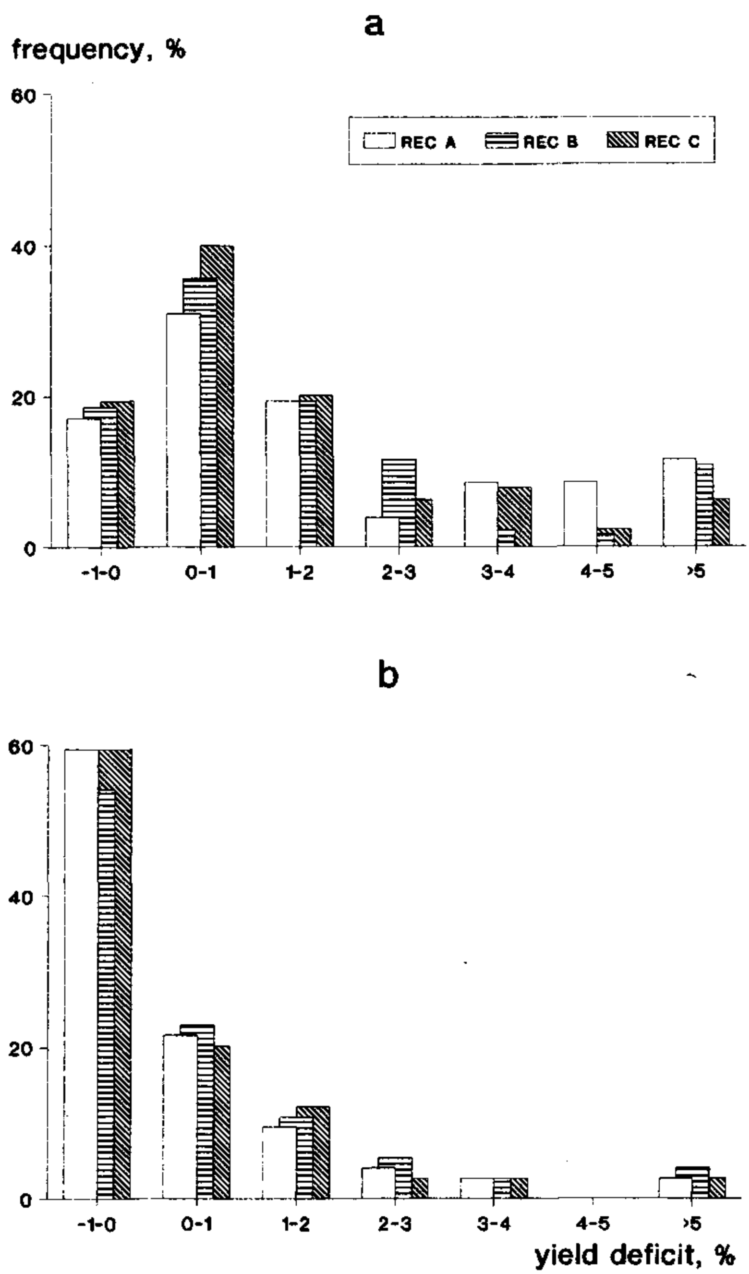

Fig. 3. Frequency distribution of the yield deficits for sugar beet (a) and potatoes (b) if REC A, REC B, and REC C had been applied to 129 sugar beet and 74 potato trials. The yield deficits are expressed as a percentage of the yield obtained with the measured optimum application rate in the trials. See Tables 1 and 2 for REC A, REC B, and REC C.

curve). When REC C was applied to sugar beet, the percentage of small yield deficits (<2 %) was highest (80 %, as compared with 74 % for REC B and 68 % for REC A) and that of large yield deficits (>5 %) was lowest (6 %, as compared with 11 % for REC B and 12 % for REC A) (Fig. 3a). For potatoes the frequency distributions of the yield deficits obtained with the various methods were similar. It is striking that the percentage of yield deficits less than 2 % was about 90 % (Fig. 3b).

All methods failed (yield deficits > 5 %) when there was a strong response to fertilizer nitrogen even though large amounts of soil mineral nitrogen were present in early spring (>100 kg N per ha in the 0-60 cm layer). In two trials with potatoes, all three methods failed when there was a negative response to fertilizer nitrogen although the soil contained only average amounts of mineral nitrogen in early spring (50-60 kg N per ha in the 0-60 cm layer), possibly due to accidental application of slurry in spring.

REC B and REC C gave good results with sugar beet, but REC A failed when the response to fertilizer nitrogen was weak or negative when large amounts of soil mineral nitrogen were present in early spring. In these situations, REC A grossly overestimated the amount of fertilizer nitrogen to be applied. REC A also failed when there was a strong response to fertilizer nitrogen at low levels of soil mineral nitrogen in early spring. The method then underestimated the amount of fertilizer nitrogen to be applied.

After application of organic manures, REC A and REC C showed good results with sugar beet, but REC B failed when the response curve clearly declined beyond its maximum. The recommendation then overestimated the amount of fertilizer nitrogen to be applied, which sometimes resulted in serious yield depressions.

REC C for sugar beet failed only once when the other methods did not. It overestimated the amount of fertilizer nitrogen to be applied on a sandy soil where without application of organic manures a rather weak response to fertilizer nitrogen occurred despite a relatively low amount of soil mineral nitrogen in early spring (32 kg N per ha in the 0-60 cm layer).

Recovery of fertilizer nitrogen

The recovery of fertilizer nitrogen by sugar beet cannot be dealt with here, because the nitrogen contents of the crop or of parts of the crop were not measured.

In 96 potato trials the nitrogen contents in the tubers were measured at harvest. The average recovery of fertilizer nitrogen in the tubers is shown in Table 5. It was

Table 5. Fertilizer nitrogen recovery by the tubers if various nitrogen fertilizer recommendation methods had been applied to potatoes. Average values of 96 trials. Standard errors are given in parentheses. See Tables 1 and 2 for meaning of REC A, REC B, and REC C.

Recommendation	Fertilizer nitrogen recovery (%)
REC A	31 (1.30)
REC B	33 (1.14)
REC C	31 (1.14)

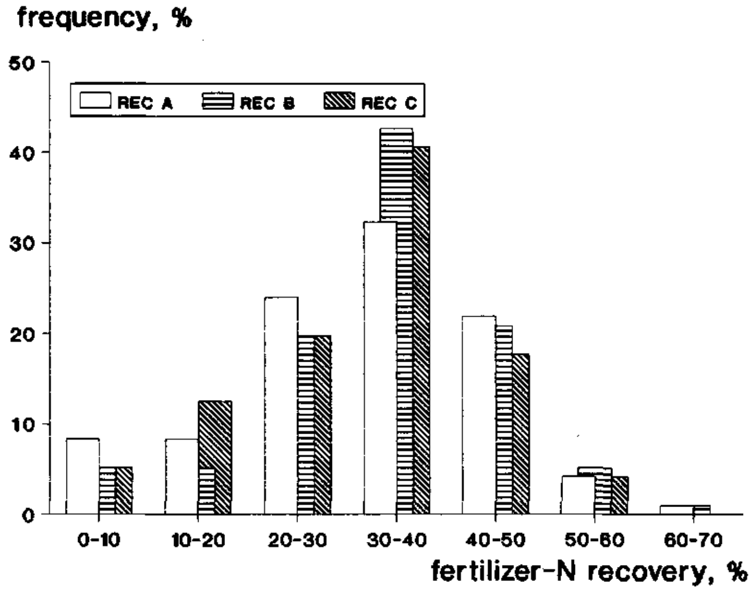

Fig. 4. Frequency distribution of the fertilizer nitrogen recovery by the potato tubers if REC A, REC B, and REC C had been applied to 96 potato trials. See Tables 1 and 2 for REC A, REC B, and REC C.

highest when REC B had been applied, but the difference with REC A and REC C was not significant and was only 2 %. The frequency distribution of the recoveries (Fig. 4) shows that the variation in recovery was higher with REC A than with REC B and REC C. Very low recoveries (0-20 %) were generally obtained on fields where the amount of nitrogen in the tubers on plots without fertilizer nitrogen was large due to large amounts of soil mineral nitrogen in spring.

Discussion

Prerequisites of nitrogen fertilizer recommendations

A nitrogen fertilizer recommendation should be high enough to guarantee a high crop yield with a high fertilizer nitrogen recovery rate, and low enough to avoid money being spent on nitrogen not needed for high yields and liable to be lost due to leaching, resulting in environmental pollution. These two prerequisites are met when a recommendation accurately predicts the economically optimum application rate of fertilizer nitrogen, i.e. the minimum amount of fertilizer nitrogen needed for maximum profit. However, due to the large inaccuracy in the determination of the optima (Neeteson & Wadman, 1987), in this paper a comparison of the various recommendation methods was not based on prediction of the optimum application rate of fertilizer nitrogen, but separately on the recommended amounts of fertilizer nitrogen and the yields obtained.

Another reason why fertilizer nitrogen rates should be used judiciously is the saving of energy which is needed for the processing of fertilizers. The energy used for fertilizer production in the Netherlands constitutes approximately 10 % of the total consumption of natural gas and 2 % of the electric energy (Anon., 1988).

Recommended rates of fertilizer nitrogen

For sugar beet the rate of fertilizer nitrogen recommended by the current method was on average 25 kg N per ha lower than the rates recommended by the fixed-rate method and the refined current method. Only at low values of soil mineral nitrogen (less than approximately 25 kg N per ha in the layer 0-60 cm, depending on soil type and application of organic manures) were the currently recommended rates higher than the other recommendations. However, the amount of soil mineral nitrogen in the 0-60 cm layer was usually larger than 25 kg N per ha, so generally lower fertilizer nitrogen rates were recommended by the current method.

For potatoes the current recommendation for fertilizer nitrogen to be applied was also lower than the other recommendations: on average 30 kg N per ha. The amount of fertilizer nitrogen currently recommended was smaller at any amount of soil mineral nitrogen in spring on sandy soils and smaller at moderate to large amounts of soil mineral nitrogen (more than approximately 30 kg N per ha in the 0-60 cm layer) on loam soils without application of organic manures and on clay soils.

It should be noted here that the current recommendations for sugar beet and potatoes are not based on calculated response curves, but on hand-drawn curves. Moreover, the data set used for designing the current recommendations was not entirely identical to that used for the other two recommendation methods. In the design of the current recommendation method for sugar beet, trials in which organic manures had been applied were excluded; for potatoes, trials with industrial potatoes were included.

Yields

On average, there was no difference in the yields obtained with the various nitrogen fertilizer recommendations. Generally, all three methods predicted fertilizer nitrogen rates with which high yields were obtained. The response curves of sugar beet and potatoes generally consist of a short segment where yield rises sharply with increasing rates of fertilizer nitrogen and a large segment where yield varies little with increasing rates (e.g. Fig. 1). The presence of this long, flat segment implies that yields were quite similar for the various nitrogen fertilizer recommendations, but more so in the case of potatoes than sugar beet, because the response curve of potatoes does not decline at the higher rates of fertilizer nitrogen. Highest tuber yields would always have been obtained with 400 kg fertilizer nitrogen per ha. Obviously, applying a fixed rate of 400 kg N per ha would seldom have been profitable and would often have increased the risk of nitrate leaching.

In 6 % (refined current method) to 11-12 % (current method and fixed-rate method) of the trials, serious yield deficits (>5 %) were obtained with sugar beet.

With potatoes it occurred in only 2-3 % of the trials. All recommendations failed when there was a strong response to fertilizer nitrogen despite the presence of large amounts of soil mineral nitrogen in early spring. Presumably, errors were made in soil sampling, soil handling and/or soil analysis. Another explanation could be that in very wet springs, heavy nitrate leaching losses occurred in the interval between soil sampling or fertilizer nitrogen application and the start of nitrogen uptake by the crop (Whitmore et al., 1987). The trials in question were conducted in 1974 and 1981. Only the spring of 1981 (especially March and May) was actually wet, while the spring of 1974 was dry.

Recovery of fertilizer nitrogen

The recovery of nitrogen by the potato tubers was not significantly affected by the various methods of recommendation, but it was highest with the current recommendation. As recovery of fertilizer nitrogen generally is higher when fertilizer nitrogen rates are lower (Greenwood & Draycott, 1988), the recovery was highest with the current method, because rates of fertilizer nitrogen recommended by this method were lowest. The recoveries were seldom higher than 50 % and averaged 31-33 % (Fig. 4, Table 5). From the average recommended fertilizer nitrogen rates (Table 3) and the average recoveries by the tubers (Table 5), the recovery by the entire crop can be estimated. When it is assumed that the maximum amount of nitrogen in the tops plus tubers of the potato crop is 1.2 times the amount of nitrogen in the tubers at harvest (Neeteson et al., 1987), and that 20 % of the total amount of nitrogen in the crop is present in the fibrous roots (Greenwood et al., 1985), it follows that the recovery of nitrogen by the entire potato crop was on average 46-50 %. The potato crop is apparently a rather inefficient user of fertilizer nitrogen. The usually poorly developed root system of the crop, together with its susceptibility to drought, are probably the main reasons for the low recovery of fertilizer nitrogen. When fertilizer nitrogen was applied at economically optimum amounts, at harvest about 30 kg more mineral nitrogen per ha was found in the soil than when no nitrogen had been applied (Neeteson et al., 1989). Sugar beet, however, is a more efficient user of fertilizer nitrogen. Fertilizer nitrogen recoveries by the tops plus beets are often found to be higher than 70 % (Prins et al., 1988). Compared with no nitrogen fertilization, the additional amount of mineral nitrogen in the soil due to nitrogen application is usually negligible at the time of harvest (Lindén, 1987; Neeteson & Ehlert, 1989).

Practical implications

For both sugar beet and potatoes the differences in performance between the methods were small, especially between the current and the refined current method. Similar results were found by Sylvester-Bradley et al. (1987a,b) when they compared more or less refined nitrogen fertilizer recommendation methods for winter wheat. There is therefore no need to replace the current method by the refined one. Moreover, the refined method would have been more expensive, because soil mineral nitrogen has to be measured in two layers instead of in one, as is the case with the current method. For sugar beet, where the contribution of soil mineral nitrogen in the 0-30 cm layer to the response to nitrogen is estimated to be 80 % of that of fertilizer nitrogen and that in the 30-60 cm layer 100 %, the problem of determining soil mineral nitrogen in two layers could be overcome by measuring it in the 0-60 cm layer and assuming that its contribution to the response to nitrogen is 90 % of that of fertilizer nitrogen.

The current method is to be preferred to the method of applying a fixed rate, because the former recommends a lower rate of fertilizer nitrogen without loss of yield.

The small improvement in the performance of the current and refined current methods, as compared with the fixed-rate method, is possibly attributable to the fact that the recommendations were made for average situations. The recommendations are too crude to be applicable to specific situations. Soil nitrogen mineralization rates during the growing season and yield levels, which have a strong impact on the fertilizer nitrogen requirement of a crop, may vary considerably from field to field. It is to be expected that site-specific nitrogen fertilizer recommendations can be given when explicit account is taken of nitrogen mineralization and crop growth. This can be done in a dynamic way with simulation models for the nitrogen cycle in the soil and for crop response to nitrogen. An example of such a model was given elsewhere (Neeteson et al., 1987).

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Chapter 5

Effect of reduced fertilizer nitrogen application rates on yield and nitrogen recovery of sugar beet and potatoes

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Effect of reduced fertilizer nitrogen application rates on yield and nitrogen recovery of sugar beet and potatoes

J. J. NEETESON

Institute for Soil Fertility, P.O. Box 30003, NL 9750 RA Haren, Netherlands

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Abstract

It was investigated how far fertilizer nitrogen application can be reduced before serious yield deficits occur, and to what extent the reductions result in higher recoveries of fertilizer nitrogen. For this purpose, 90, 75, 50 and 0 % of the fertilizer nitrogen rates recommended according to the current method were retrospectively applied to 150 sugar beet and 98 potato trials conducted earlier. When it is assumed that the chance of yield deficits larger than 5 % is not allowed to exceed 5 %, the currently recommended fertilizer nitrogen application rate for sugar beet cannot be lowered, but the rate for potatoes can be reduced by about 25 %. The average yield deficit will then be about 1.5 %, and the recovery of fertilizer nitrogen by the potato tubers will be about 40 %. The effect of a change in the ratio of the cost of fertilizer nitrogen to the price of produce on the economically optimum application rate of fertilizer nitrogen was also investigated; it was determined on the basis of the average response curves of the 150 sugar beet and 98 potato trials. A change in the ratio of the cost of fertilizer nitrogen to the price of produce had a much smaller effect on the optimum application rate of fertilizer nitrogen for sugar beet than on that for potatoes. A fivefold increase in the ratio decreased the optimum for sugar beet by only 20 %, for potatoes by 50 %. However, it also considerably decreased farm income. The decrease was more than Dfl. 400 per ha for sugar beet and more than Dfl. 800 per ha for potatoes.

Keywords: crop yield, fertilizer nitrogen recovery, potatoes, price ratio, sugar beet

Introduction

The performance of various methods used to make nitrogen fertilizer recommendations for sugar beet and potatoes have recently been evaluated (Neeteson, 1989). The methods consisted of (1) applying a fixed rate in all situations, (2) the current Dutch method, which takes only the amount of soil mineral nitrogen present in the soil in early spring into account, and (3) a refinement of the current method, which also takes soil type and recent applications of organic manures into account. It was shown that the methods differed in the recommended rate of fertilizer nitrogen, the current method recommending the lowest rates. The three methods were not significantly different with respect to yields obtained and recovery of fertilizer nitrogen. Despite differences in fertilizer nitrogen rates the yields were similar due to the presence of a long, flat segment in the response curves of sugar beet and potatoes.

In this paper it is investigated how far rates of fertilizer nitrogen application can be lowered before serious reductions in yield occur, and to what extent the reductions result in higher recoveries of fertilizer nitrogen. For this purpose, 90, 75, 50 and 0 % of the fertilizer nitrogen rates recommended according to the current method were retrospectively applied to 150 sugar beet and 98 potato trials conducted earlier (Neeteson & Zwetsloot, 1989). The yields and recoveries of fertilizer nitrogen were determined from the response curves obtained in the trials.

Since the present recommendations are based on a fixed ratio P of the cost of 1 kg fertilizer nitrogen to the price of 1 tonne produce, viz. 0.01 for sugar beet and 0.006 for potatoes (Neeteson, 1989), the recommendations should be adjusted if a change in the value of P would occur. It is quite possible that the value of P will increase in the future when the current low prices of fertilizer nitrogen rise, not only due to higher energy costs, but possibly also due to a levy imposed on fertilizers (Williams, 1988). Therefore, in the present paper the effect of any change in the value of P on the economically optimum application rate of fertilizer nitrogen was evaluated using the average response curves of the 150 sugar beet and 98 potato trials.

Materials and methods

Four reduced rates of fertilizer nitrogen recommended with the current advisory method (90, 75, 50, and 0 %) were retrospectively applied in 150 sugar beet and 98 potato trials.

The current advisory method for nitrogen fertilization is based on the amount of mineral nitrogen present in the soil in early spring (Anon., 1986). The recommendations used in this paper (Table 1) were adapted from the recommendations given in Anon. (1986) in such a way that the ratio P of the cost of 1 kg fertilizer nitrogen to

Table 1. Current nitrogen fertilizer recommendations for sugar beet and potatoes. N_{rec} = recommended rate; $N_{m0\text{-}30}$, and $N_{m0\text{-}60}$ are the amounts of soil mineral nitrogen in the layers 0-30, and 0-60 cm, respectively. P is set at 0.01 for sugar beet and 0.006 for potatoes. All amounts are expressed in kg N per ha.

Crop	Soil type(s)	Organic manures	N_{rec}
Sugar beet	sand, loam, clay	no, yes[1]	$200 - 1.7\ N_{m0\text{-}60}$[2]
	sand, loam, clay	green manures	$170 - 1.7\ N_{m0\text{-}60}$[3]
Potatoes	sand	no, yes	$350 - 1.8\ N_{m0\text{-}30}$
	loam, clay	no, yes	$320 - 1.1\ N_{m0\text{-}60}$

[1] With the exception of green manures.
[2] When $N_{m0\text{-}60}$ is 100-150, N_{rec} is fixed at 30, when $N_{m0\text{-}60} > 150$, N_{rec} is 0.
[3] When $N_{m0\text{-}60}$ is 85-135, N_{rec} is fixed at 30, when $N_{m0\text{-}60} > 135$, N_{rec} is 0.

the price of 1 tonne produce was 0.01 for sugar beet and 0.006 for potato (Neeteson, 1989).

In the trials, soil mineral nitrogen was measured in various layers in early spring, and yield was measured at six or seven levels of fertilizer nitrogen. In 96 potato trials the amount of nitrogen in the tubers at harvest was measured. Details of the experimental design were given elsewhere (Neeteson & Wadman, 1987; Neeteson & Zwetsloot, 1989).

The yield associated with each recommendation was calculated from the response curve of each individual trial. For sugar beet modified exponential and for potatoes exponential response curves were fitted to the measured yields (Neeteson & Zwetsloot, 1989). For sugar beet the yields were expressed as fresh beet yields with a sugar content of 16 % (Neeteson & Wadman, 1987), and for potatoes as fresh tuber yields. The nitrogen uptake by the potato tubers was found by interpolating between the measured amounts of nitrogen in the tubers at the fertilizer nitrogen levels actually applied. The recovery was calculated according to the difference method, i.e. the difference between nitrogen uptake with and without fertilizer nitrogen application, expressed as a percentage of the amount of fertilizer nitrogen applied. The recovery without fertilizer nitrogen, viz. an infinitely small amount of fertilizer nitrogen, was calculated from the tangent drawn to the nitrogen uptake response curve at zero-N application.

The effect of the value of the ratio P on the economically optimum application rate of fertilizer nitrogen was determined from the average response curves of the 150 sugar beet and 98 potato trials, which were given in another paper (Neeteson, 1989). The optima and their 95 % confidence intervals were calculated for various values of P (ranging from 0.005 to 0.04 for sugar beet, and from 0.005 to 0.025 for potatoes) according to Neeteson & Zwetsloot (1989).

Results

Reduced rates of fertilizer nitrogen

Yields

The average yields obtained with the current nitrogen fertilizer recommendations and with reduced rates of fertilizer nitrogen are shown in Table 2. When the rates were reduced by 25 %, the average yields of both sugar beet and potatoes did not differ significantly from the yields obtained with the recommended rates. When 50 % of the recommended rates was applied, average sugar beet and potato yields differed significantly ($P < 0.05$) from the yields obtained with the recommended rates, but the differences were relatively small: 2.5 t ha^{-1}, i.e. 4 %.

The frequency distributions of the yield deficits with the reduced application rates of fertilizer nitrogen, i.e. the deviations of the yields from those obtained with the recommended rates of fertilizer nitrogen, were quite similar for sugar beet and potatoes (Fig. 1). With increasing reductions in application rates, the percentage of small deficits (<1 %) sharply decreased, whereas that of large yield deficits (>5 %) sharply increased. In about 6 % of the sugar beet and potato trials large

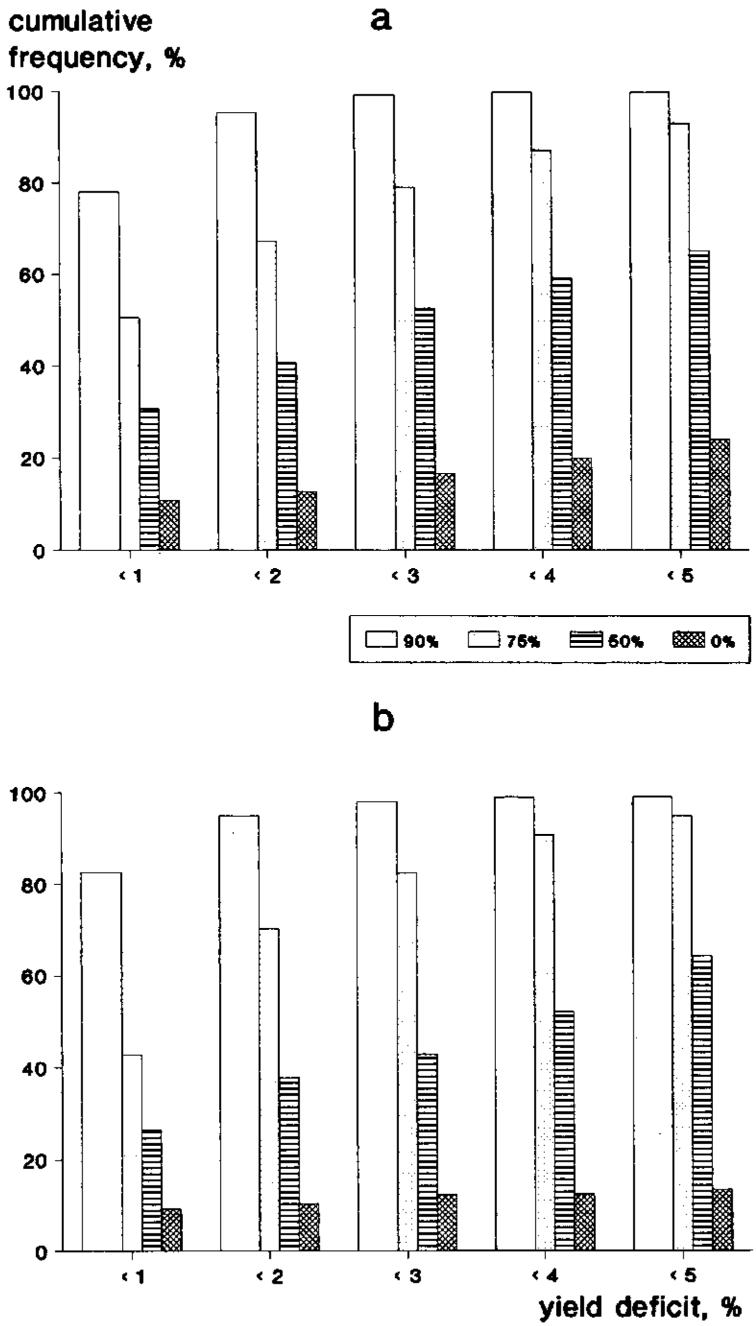

Fig. 1. Frequency distribution of the yield deficits for sugar beet (a) and potatoes (b) if 90, 75, 50 or 0 % of the fertilizer nitrogen recommended had been applied to 150 sugar beet and 98 potato trials. The yield deficits are expressed as a percentage of the yield obtained with the recommended application rate of fertilizer nitrogen in the trials.

Table 2. Yields of sugar beet and potatoes for various reductions in the recommended fertilizer nitrogen rates. Average values of 150 sugar beet and 98 potato trials. Standard errors are given in parentheses.

Fertilizer N applied (% of recommended rate)	Sugar beet		Potatoes	
	yield ($t\ ha^{-1}$)	yield deficit ($t\ ha^{-1}$)	yield ($t\ ha^{-1}$)	yield deficit ($t\ ha^{-1}$)
100	63.8 (0.89)	0	56.8 (0.88)	0
90	63.5 (0.90)	− 0.3	56.5 (0.88)	− 0.3
75	62.9 (0.92)	− 0.9	55.9 (0.88)	− 0.9
50	61.2 (0.96)	− 2.6	54.4 (0.91)	− 2.4
0	53.3 (1.17)	−10.5	45.1 (1.19)	−11.7

yield deficits occurred when 75 % of the nitrogen recommended was applied. When 50 % of the nitrogen recommended was applied, this occurred in about 35 % of the trials.

Recovery of fertilizer nitrogen

The recovery of fertilizer nitrogen by sugar beet is not dealt with here, because the nitrogen contents of the crop or parts of the crop were not measured.

The average fertilizer nitrogen recoveries by the potato tubers obtained with the reduced rates of fertilizer nitrogen are shown in Table 3. When 90 % of the recommended rate was applied, the average recovery of fertilizer nitrogen did not significantly differ from the recovery at the recommended rate. When 75 % and 50 % of the recommended rates were applied, however, the average recovery increased significantly ($P < 0.001$) from 33 to 39 and 44 %, respectively.

In Fig. 2 the frequency distributions of the increases in fertilizer nitrogen recovery by the tubers obtained with the reduced rates of fertilizer nitrogen are shown, i.e. the difference between the recovery at the reduced rates and the recommended

Table 3. Fertilizer nitrogen recovery by the potato tubers for various reductions in the recommended fertilizer nitrogen rates. Average values of 96 trials. Standard errors are given in parentheses.

Fertilizer N applied (% of recommended rate)	Fertilizer N recovery	
	(%)	difference from recommended rate (%)
100	33.2 (1.14)	0
90	35.4 (1.19)	2.2
75	38.7 (1.25)	5.5
50	44.3 (1.36)	11.1
0	52.6 (1.53)	19.4

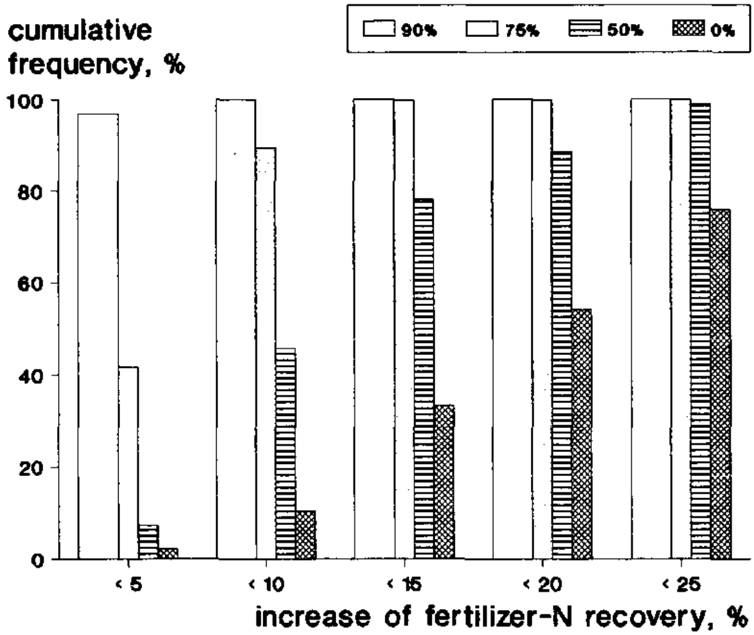

Fig. 2. Frequency distribution of the fertilizer nitrogen recovery by the potato tubers if 90, 75, 50 or 0 % of the fertilizer nitrogen recommended had been applied to 96 potato trials.

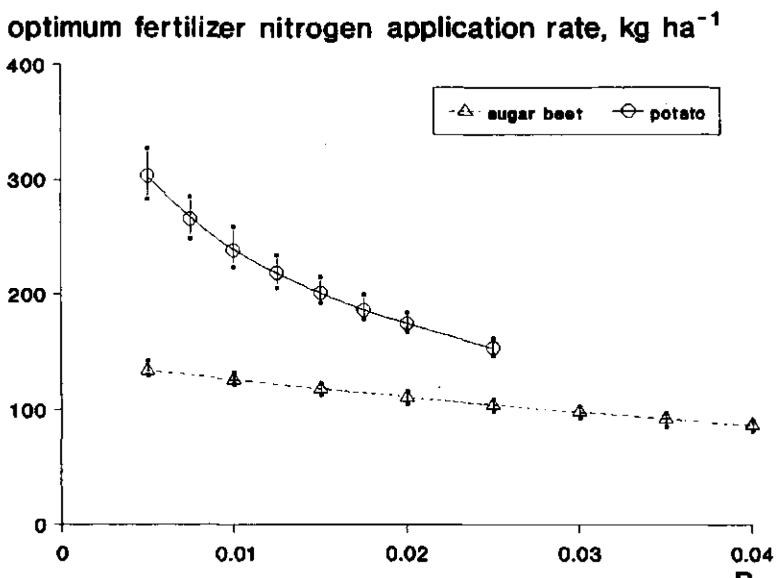

Fig. 3. Effect of the ratio P of the cost of 1 kg fertilizer nitrogen to the price of 1 tonne produce on the average economically optimum application rate of fertilizer nitrogen for sugar beet and potatoes. I = 95 % confidence interval for the optima.

Table 4. Average effect of fertilizer nitrogen costs on gross financial yield of sugar beet and potatoes. The price of 1 tonne beets is fixed at Dfl. 100 and the price of 1 tonne potato tubers at Dfl. 200. N_{op} = economically optimum application rate of fertilizer nitrogen, Y = yield.

Crop	Cost of 1 kg fertilizer N (Dfl.)	N_{op} (kg N per ha)	Y (t ha^{-1})	Y − N_{op} (Dfl.)	Yield deficit (Dfl.)
Sugar beet	1	134	63.72	6238	0
	2	126	63.67	6115	123
	3	118	63.58	6004	234
	4	111	63.45	5901	337
	5	104	63.30	5810	428
Potatoes	1	303	56.89	11075	0
	2	238	56.42	10808	267
	3	201	55.96	10589	486
	4	174	55.49	10402	673
	5	153	55.02	10239	836

rate. When 90 % of the recommended rate was applied, the increase in recovery was seldom higher than 5 %. At 75 % of the rate recommended, the increase was between 0 and 15 %, whereas large increases (>15 %) occurred at 50 % of the rate recommended or without fertilizer nitrogen application.

Ratio between the cost of fertilizer nitrogen and the price of produce

The relationship between the ratio P of the cost of fertilizer nitrogen and the price of produce, and the economically optimum application rate for fertilizer nitrogen of sugar beet and potatoes is shown in Fig. 3. With increasing values of P, for instance due to increasing costs of fertilizer nitrogen at constant prices of produce, the optima decreased. The effect of P on the optimum was much smaller for sugar beet than for potatoes: a threefold increase in P resulted in a decrease in the optimum of about 30 kg N per ha for sugar beet, but of about 100 kg N per ha for potatoes.

With the results presented in Fig. 3 and the yields obtained with the various optimum application rates of fertilizer nitrogen, the average effect of increasing costs of fertilizer nitrogen on the gross monetary yields of sugar beet and potatoes were calculated (Table 4). In the calculations it was assumed that all costs other than nitrogen fertilizer costs do not change with decreasing application rates of fertilizer nitrogen. The results of Table 4 clearly show that increasing nitrogen fertilizer costs have a strong impact on farm income.

Discussion

Reduced rates of fertilizer nitrogen

When the application rates of fertilizer nitrogen recommended for sugar beet and

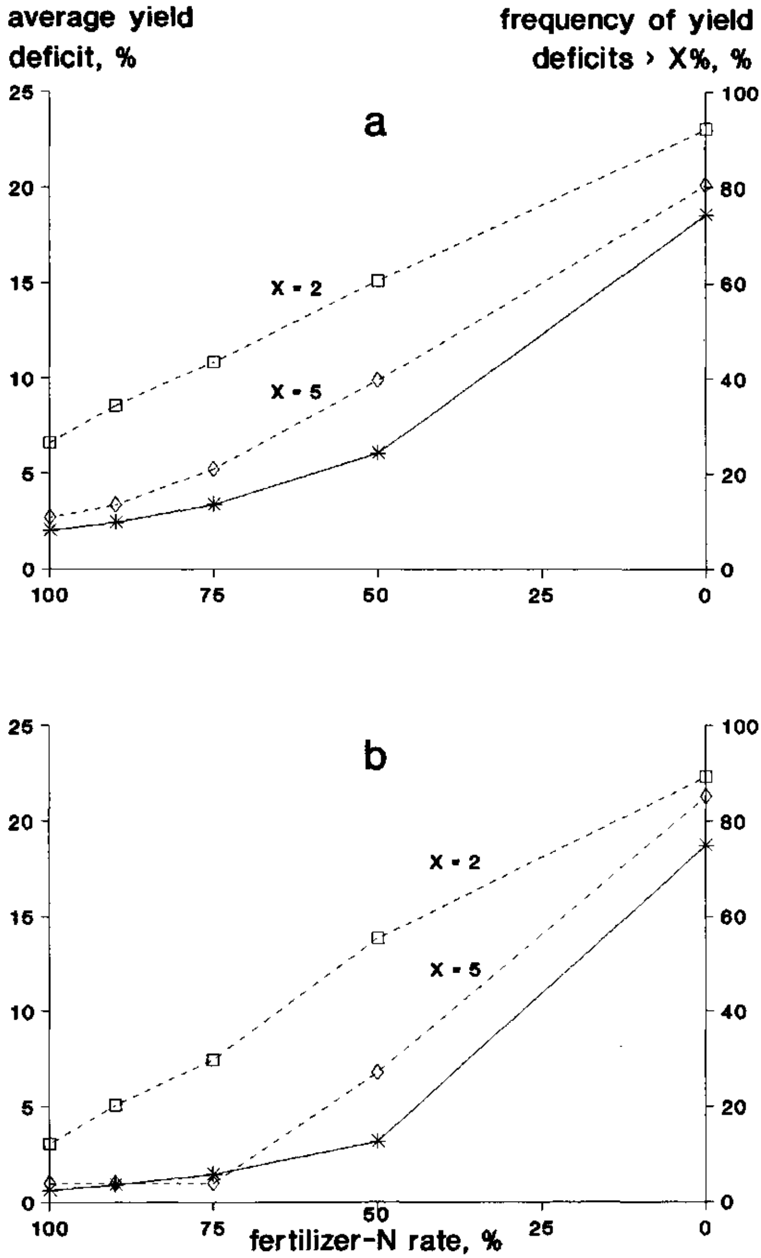

Fig. 4. Relationship between reduced fertilizer nitrogen rates, and average yield deficits (solid lines) and the frequency of occurrence of yield deficits (broken lines) in sugar beet (a) and potatoes (b). The relationships are based on 150 sugar beet and 98 potato trials. The yield deficits are expressed as a percentage of the yield obtained with the measured optimum application rate of fertilizer nitrogen in the trials.

potatoes were reduced by 25 %, yields were obtained which on average did not differ from those obtained with the recommended rates (Table 2), but the chance of getting serious yield deficits (>5 %) increased by about 5 % (Fig. 2). Apparently, the current nitrogen fertilizer recommendations for sugar beet and potatoes can be reduced without substantial loss of yield. How far the recommendations can be reduced can be derived from the relationships between the reduction in fertilizer rate, and the average yield deficit and the frequency of occurrence of yield deficits (Fig. 4). In Fig. 4 the yield deficits are not expressed as a percentage of the yield obtained with the current recommendation as was done in Table 2 and Fig. 1, but as a percentage of the yield obtained with the measured optimum application rate of fertilizer nitrogen in the trials. When it is assumed that an average yield deficit of 2 % is acceptable, the current recommendation for sugar beet cannot be lowered, because the average yield deficit with the recommendation already amounted to 2 % (Fig. 4a), but the recommendation for potatoes can be reduced by 32 % (Fig. 4b). The chance of serious yield deficits is then about 11 % (Fig. 4b). When it is assumed, however, that the chance of serious yield depressions is not allowed to exceed 5 %, the current recommendation for sugar beet cannot be lowered (Fig. 4a), but for potatoes it can be reduced by 27 % (Fig. 4b). In that case the average yield deficit will be 1.7 % (Fig. 4b), and the recovery of fertilizer nitrogen by the potato tubers will be about 40 % (Table 3).

From the farmer's point of view no measures should be taken which reduce yields of sugar beet and potatoes, because these crops have a strong impact on the income of Dutch farmers. When sugar beet and potatoes are grown in a four-year rotation with winter wheat and spring barley, sugar beet contribute up to 30 % and potatoes up to 35 % of the total net monetary yield; these figures are about 35 and 45 % when sugar beet and potatoes are grown in a three-year rotation with winter wheat (Anon., 1988).

It should be noted here that the effects of reduced fertilizer nitrogen rates shown in this paper are short-term effects. Because the amount of crop residues remaining in the soil will decrease with decreasing inputs of fertilizer nitrogen, resulting in decreasing contributions of nitrogen mineralized from those residues, it is to be expected that the long-term effects of reduced nitrogen applications will be larger.

Ratio between the cost of fertilizer nitrogen and the price of produce

The data shown in Fig. 3 can be used to adjust nitrogen fertilizer recommendations for sugar beet and potatoes to changing costs of fertilizer nitrogen and/or changing prices of produce. A change in the ratio P had a much smaller effect on the economically optimum application rate for sugar beet than on that for potatoes. This is due to the relatively steep course of the response curve of sugar beet (Neeteson, 1989). As the shapes of response curves of cereals (Dilz, 1981; Sylvester-Bradley et al., 1983) are generally similar to that of sugar beet, it is to be expected that a change in the value of P will also have relatively little effect on the economically optimum application rate of fertilizer nitrogen for cereals.

If a levy would be imposed on nitrogen fertilizer to restrict the use of nitrogen fertilizers in order to protect the environment, its effects on the use of nitrogen fertilizers for sugar beet would be small. A fivefold increase in the costs of fertilizer nitrogen would decrease the economically optimum application rate of fertilizer nitrogen by only about 20 % (Table 4). For potatoes the effects would be much larger: a fivefold increase in fertilizer nitrogen costs would halve the optimum application rate (Table 4). The effects on farm income, however, would be considerable (Table 4). Imposing a levy on fertilizers is therefore only justified if the decrease in fertilizer use would clearly reduce the environmental effects of fertilizer application. As long as fertilizer nitrogen is applied according to the recommendations, it is doubtful if reduced applications to sugar beet would affect nitrate leaching. Due to the high nitrogen uptake efficiency of the crop it has been found that the amount of soil mineral nitrogen at harvest is not affected by the amount of fertilizer nitrogen applied (Lindén, 1987; Neeteson & Ehlert, 1989). Thus, assuming that the sugar-beet tops are removed from the field, leaching of fertilizer nitrogen in autumn and winter is not likely to occur. Reduced applications to potatoes perhaps lower the amount of nitrate leached, because fertilizer nitrogen application may increase soil mineral nitrogen at harvest, although experimental evidence is scarce (Prins et al., 1988).

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Chapter 6

A dynamic model to predict yield and optimum nitrogen fertilizer application rate for potatoes

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A dynamic model to predict yield and optimum nitrogen fertilizer application rate for potatoes

J. J. NEETESON[1], D. J. GREENWOOD[2] & A. DRAYCOTT[2]

[1] Institute for Soil Fertility, P.O. Box 30003, NL 9750 RA Haren, Netherlands
[2] Institute of Horticultural Research, Wellesbourne, Warwick CV35 9EF, UK

SUMMARY

A dynamic model for the response of potatoes to nitrogen fertiliser is described which has inputs that are generally available to growers and advisers. It consists largely of previously published relationships for the various processes, but also includes others that have been derived from recent field experiments. The model was used to predict the effects of seven levels of nitrogen fertiliser on the dry weights of tubers in each of 61 field experiments that were entirely independent of those used for developing the model.

The validity of the model was tested by several quite different procedures including ones based on identifying statistically significant differences between predicted and measured optimum nitrogen fertiliser levels, differences in the yields with individual levels of fertiliser, and trends in the differences between predicted and measured yields with increasing levels of fertiliser. According to these criteria the model gave a reasonably good description of the data. In one test of the model only those inputs (e.g. predicted weather) that were available to the adviser at the time advice is required were used. The optimum rates of nitrogen fertiliser were predicted for each of the 61 experiments. With these rates yields of tuber dry weight were within 2% of those obtained with the measured optimum level of nitrogen fertiliser in 84% of the experiments. Fertiliser advice based on this model is about as good as that obtained with the best system currently available in the Netherlands.

The treatment in the model of inter-site variation in the mineralisation rate and the recovery of the mineral nitrogen by the shoots and tubers was superficial. As this variation was found to be considerable, there are possibilities for improving the model and thus of providing a better basis for practical advice than is available at present.

1. INTRODUCTION

In Western Europe current nitrogen fertiliser recommendations for arable crops are generally based on measurement of soil mineral nitrogen in early spring (N_{min}-method) or on soil mineral nitrogen in early spring, expected supply of mineral nitrogen by the soil, and expected yield level of the crop (balance-sheet method) [11]. The recommendations are based on relationships between values of the relevant parameters at the start of the growth period and at final harvest of the crop. What is happening between the start and the end of the growth period is regarded as occurring in a "black box". As many dynamic processes take place during crop growth, account needs to be taken of these processes and their interactions. With simulation models it should be possible to calculate, on a daily basis, the growth and the nitrogen uptake of a crop and the nitrogen supply to a crop using standard weather data, and field and crop parameters as inputs. A simulation model could be used as a tool to indicate the nitrogen fertiliser requirement of a crop at any time during the growth period. A simulation model could thus add the 'time' element to nitrogen fertiliser advice as well as providing a better basis for it.

The aim of the present paper is to describe the current state of development of a dynamic model for the response of potatoes to nitrogen fertiliser. The model presented here is a new version of the model of Greenwood *et al.* [14, 15]. Tuber yields at seven nitrogen fertiliser levels of 61 field experiments with potatoes will be predicted. On the basis of the predicted yields for each experiment a predicted nitrogen fertiliser response curve will be calculated from which an optimum nitrogen fertiliser application rate will be derived. It should be noted that the 61 field experiments were independent of the experiments used in the development of the model.

2. THE MODEL

The potato crop is visualised as growing on soil that is divided into 5 cm thick layers. The number of layers depends on the maximum rooting depth, which is given as an input parameter. As the crop grows the roots penetrate more and more of these layers and are able to extract mineral nitrogen from them. It is assumed that all mineral nitrogen is in the form of nitrate, because in Dutch soils the rate of nitrification is generally much higher than the rate of mineralisation. Moreover, fertiliser ammonium is usually nitrified within two weeks of being applied. The model calculates on a daily basis:

* potential increase in total dry weight
* actual increase in total dry weight
* mineralisation of soil organic matter
* soil moisture content
* leaching of nitrate
* depth of rooting
* potential uptake of nitrogen
* actual uptake of nitrogen
* removal of nitrate by roots from each layer of soil
* partition of dry weight between tuber and foliage
* partition of nitrogen between tuber and foliage

The field-dependent inputs required by the model are:

* amount of soil mineral nitrogen at the onset of spring
* time and rate of nitrogen fertiliser application
* time of planting
* expected maximum tuber yield
* expected maximum depth of rooting
* soil type
* daily values of soil temperatures at 10 cm depth and precipitation surplus between time of sampling for the determination of soil mineral nitrogen and the time when crop growth ceases.

All input parameters are readily available to farmers.

The model consists largely of previously derived relationships [14, 15]. For the sake of completeness these relationships will first be described briefly, together with relationships that were modified. Next, the derivation of new relationships will be described in detail. The symbols used and their definitions are given in the Appendix.

2.1. Previously derived relationships

Unless otherwise stated, the previously derived relationships were described by Greenwood *et al.* [14, 15].

2.1.1. Potential increase in total dry weight

The potential increase in dry weight of potato tops plus tubers over an increment in time is calculated from

$$\Delta W / \Delta T = K_2 W / (K_1 + W) \tag{1}$$

Where W is the total weight of dry matter (t ha^{-1}), T is time (d) and K_1 (t ha^{-1}) and K_2 (t ha^{-1} d^{-1}) are coefficients [12]. To decrease errors of integration, W is set equal to its value at the start of the day plus half of its increase during the previous day. ΔT is set equal to 1 day and K_1 to 1 t ha^{-1}. K_2 is calculated from the integral of Equation (1) and the expected maximum total dry weight (input parameter), the dry weight at emergence (set equal to 0.5 t ha^{-1}), the time of emergence (see 2.3.2.) and the time when growth ceases (input parameter).

2.1.2. Actual increase in total dry weight

The actual increase in total dry weight is the product of the potential increase in total dry-matter yield and a growth factor G_F which changes from day to day. G_F depends on the actual %N in the total dry matter, P_W, on the minimum %N in the total dry matter needed for the maximum growth rate, P_M, and on the %N in the total dry matter when growth ceases, P_O. If $P_W > P_M$, G_F is set equal to 1. Otherwise

$$G_F = (P_W - P_O) / (P_M - P_O) \tag{2}$$

assuming that crop growth rate linearly falls with the decline in P_W when the %N is lower than needed for the maximum growth rate. P_M is defined as

$$P_M = 1.35\,(1 + 3\,e^{-0.26\,W}). \tag{3}$$

It is assumed that P_O equals 0% at the start of crop growth and increases to 0.8% at maturity in proportion to the tuber dry weight expressed as a fraction of the total crop dry weight (calculated from Equation 7 (section 2.2.4)).

2.1.3. Evapotranspiration and soil moisture content

The water balance of the soil is calculated as described previously [17]. The methods used are based on those given by Belmans *et al.* [5], Black *et al.* [6], Hillel [18], and Siddig [24].

Evapotranspiration is calculated as the sum of the water lost through evaporation from the soil surface and that transpired from the crop. Total daily evapotranspiration, E_T (mm), is calculated as

$$E_T = f_r E_C + (1 - f_r) E_S \tag{4}$$

where f_r is the fraction of soil covered by the crop, E_C is the transpiration per unit area of crop (mm), and E_S is the evaporation from bare soil per unit area of soil (mm). The fraction f_r is set equal to 0.66 * dry weight of the foliage (t ha^{-1}), but is never allowed to exceed 1.

E_C is assumed to be the potential maximum transpiration rate, E_O, when the soil moisture deficit is less than a critical value and to decline linearly with increasing soil moisture deficits until an upper critical deficit is reached where transpiration ceases. The critical soil moisture deficits are estimated from results obtained previously [14]: 0.146 and 0.156 cm for sandy soils, 0.202 and 0.212 for loamy soils and 0.111 and 0.171 cm for clayey soils. The values of the critical soil moisture deficits are all per cm of rooting depth. The rate of loss of water from the bare soil is calculated for each day from the potential evaporation from an open water surface and the apparent soil moisture deficit.

2.1.4. Leaching of nitrate

For any day when the soil is at field capacity and rainfall exceeded evapotranspiration the redistribution of mineral nitrogen is calculated according to Burns' model [7]. Upward movement of nitrate is calculated from Burns' model by assuming that it takes place throughout the cross-sectional area when fractional crop cover is less than or equals 0.5, and does not take place at all when crop cover exceeds 0.5. It is assumed that all mineral nitrogen is in the form of nitrate.

2.1.5. Potential uptake of nitrogen

The potential uptake of nitrogen by the crop is calculated as the maximum possible amount of nitrogen in the crop at the end of the day less the amount 24 hours earlier. It is assumed that the %N in total dry matter could be about 20% greater than the minimum %N needed for maximum growth, P_M. The maximum possible %N was thus set at 1.2 P_M. The calculation of P_M is given in Equation (3).

2.1.6. Removal of nitrate by the crop from each layer of soil

It is assumed that nitrate is first removed from the uppermost 5 cm layer until the amount in the soil falls to a critical amount below which the roots are unable to absorb the nitrogen. This critical amount is taken to be 0.46 kg nitrogen per ha per cm, which is the minimum found experimentally [14]. When this available nitrate is exhausted, roots remove nitrate from the next layer and so on down the profile.

2.2. Modified relationships

2.2.1. Mineralisation of soil organic matter

We use the term "apparent mineralisation" in preference to "mineralisation", because we include any losses of nitrogen due to immobilisation, denitrification, ammonia volatilisation, and fixation by clay minerals in our mineralisation rates.

The rate of apparent mineralisation of soil organic mater, dM_N / dT, is considered to be constant for constant environmental conditions throughout the growth period. In experiments of the late 1960s and early 1970s an average value of 0.78 kg nitrogen per ha per day in the 0-100 cm layer was found [14]. As nowadays crop yields are higher than those in the late 1960s and early 1970s, the amount of crop residues will also be larger. When crop residues are larger, the mineralisation rate should also be higher, because crop residues are the "young" organic matter [19] which is responsible for most of the mineralisation. Another cause of faster mineralisation is the increased application of slurry to arable fields. In the Netherlands the application of slurry has increased dramatically since the late 1960s and the early 1970s. In this paper the constant rate of apparent mineralisation is set rather arbitrarily at 1 kg nitrogen per ha per day, assuming a temperature of 12°C, which is the average soil temperature at 10 cm depth in the Netherlands between March and August [1]. The daily rate of apparent mineralisation is corrected for the actual temperature according to Van Veen and Frissel [27].

Apparent mineralisation is assumed to decline with depth in the same way as the amount of roots of a good crop because that roots are the main precursors of the readily decomposable fraction of organic matter. In past work [13] it has been found that root density declines exponentially with depth and that the depth of the soil containing any given proportion of roots is linearly related to plant mass. We assume that the rate of apparent mineralisation dM_N / dT to a depth x cm from the soil surface is defined by

$$dM_N / dT = m\,(1 - e^{-Qx}) \qquad (5)$$

where m is the value of the constant rate of apparent mineralisation. Q is arbitrarily set equal to 0.0738 cm^{-1}, which means that 97.5% of the total mineralisation is assumed to take place in the 0-50 cm layer of soil.

Temporary "disappearance" of fertiliser nitrogen shortly after its application [21] is ignored.

2.2.2. Depth of rooting

For potatoes the depth of root penetration, i.e. depth of soil containing 90% of the roots, increases roughly linearly with increase in W until a stage is reached after which no further penetration occurs [10]. It is assumed that root penetration starts at 18 cm depth from the soil surface and continues in proportion to W until rooting depth is maximum. The maximum depth of rooting is given as an input parameter.

2.2.3. Actual uptake of nitrogen

The actual uptake of nitrogen by the crop is calculated from the potential uptake and the amount of available nitrate to the depth of rooting. It is assumed that the amount of nitrate available to the crop is equal to the difference between the actual amount of soil mineral nitrogen and a critical amount below which the roots are unable to absorb the nitrogen. This critical amount is taken to be 0.46 kg nitrogen per ha per cm (see also 2.1.6.).

When plants are small they are able to absorb mineral nitrogen only from the fraction F_R of the cross-sectional area to the depth of rooting. At the start of growth F_R is arbitrarily set at a value of 0.1. On the basis of data of Asfari [4] it is assumed that when W = 0.6 t ha^{-1}, potato roots are able to absorb all mineral nitrogen. The absorption coefficient F_R is therefore calculated as

$$F_R = 0.1 + 0.9\,W / 0.6 \qquad (6)$$

with F_R set equal to 1 when its calculated value exceeds 1.

The actual uptake of nitrogen by the crop is considered equal to the potential uptake when the amount of available nitrate within the rooting zone exceeds the potential uptake. Otherwise the actual uptake is set equal to the amount of available nitrate within the rooting zone.

2.2.4. Partition of dry weight between foliage and tubers

The partition of dry weight between foliage and tubers is calculated from the ratio R of the dry weight of the foliage to that of the foliage plus tubers from the equation

$$R = e^{(0.3543 - 0.0193\,(T - T_E))} - 0.0759 \tag{7}$$

where T_E is time of emergence of the potato crop (section 2.3.2.). In previous work [14] T_E could not be calculated. The start of growth was then estimated by calculating the "effective planting time" from the experimental data, the time when $W = 0.0067$ t ha^{-1}.

2.2.5. Partition of nitrogen between foliage and tubers

The partition of nitrogen between foliage and tubers is calculated from the ratio R_U of the amount of nitrogen in the foliage to that in the foliage plus tubers from the equation

$$R_U = 1.1409 - 0.009364\,(T - T_E) \tag{8}$$

In previous work T_E was calculated as the "effective planting time" (see 2.2.4.)

2.3. New relationships

2.3.1. Experiments

New relationships to describe nitrogen response of potatoes were derived from a group of 15 experiments (experiments IB-0014) and a group of 3 experiments (experiments IB-0024/0027).

Experiments IB-0014

In the period 1968-1981 15 nitrogen fertiliser experiments with potatoes (*Solanum tuberosum* L., cv. Bintje) were conducted. In each experiment three rates of nitrogen fertiliser were applied: no nitrogen fertiliser, a medium rate and a high rate (Table 1). Nitrogen fertiliser was applied as calcium nitrate (82-87% $Ca(NO_3)_2$). After soil analysis each experimental field was uniformly fertilised with potassium and phosphate according to recommendations (the former and current recommendations are described in [3]).

With the exception of two experiments, all experiments were conducted on the experimental farm "Dr H. J. Lovinkhoeve" of the Institute of Soil Fertility. The farm is located in Marknesse (Noordoostpolder, The Netherlands). The soil type is a heavy loam with an organic matter content of about 2% (Table 2). The two experiments which were not conducted on the "Dr. H. J. Lovinkhoeve" were carried out in 1976 on the experimental farm OBS in Nagele (also Noordoostpolder), about 10 km from Marknesse.

During the growth period several harvests were carried out (Table 1) to determine fresh and dry weights, and nitrogen contents of the potato tops and tubers. After drying at 105°C, the nitrogen contents of the tops were determined according to the "phenolate-method" [28], those of the tubers in fresh material according to the "salicylate-method" [28]. Plot size was 6×4.5 m^2 and there were two or three replicates.

Experiments IB-0024/0027

In the period 1982-1985 three nitrogen fertiliser experiments with potatoes (cv. Bintje) were conducted also at the "Dr. H. J. Lovinkhoeve" farm. In each experiment three rates of nitrogen fertiliser were applied: no nitrogen fertiliser, a medium rate and a high rate (Table 3). Nitrogen fertiliser was applied as ammonium nitrate limestone. After soil

Table 1: Values of the medium and high nitrogen fertiliser application rates and the number of harvests (including final harvest) of the IB-0014 experiments.

Year	Nitrogen fertiliser application rate (kg ha^{-1})		Number of harvests
	Medium	High	
1968	100	200	12
1969	100	200	13
1970	120	240	12
1971	120	240	12
1972	120	240	7
1973	120	240	8
1974	120	240	6
1975	120	240	6
1976-A	120	240	7
1976-B	120	240	7
1977	120	240	6
1978	120	240	6
1979	120	240	6
1980	120	240	6
1981	160	320	6

Table 2: Soil characteristics at the "Dr. H. J. Lovinkhoeve". All values pertain to the 0-25 cm layer.

Fraction < 2 μm (%)	19
Fraction < 16 μm (%)	34
Fraction < 50 μm (%)	82
Fraction > 210 μm (%)	1
Organic matter content (%)	2.3
Total N-content (%)	0.11
pH-KCl	7.4

Table 3: Values of the medium and high nitrogen fertiliser application rates and the number of harvests (including final harvest) of the IB-0024/0027 experiments

Trial	Year	Nitrogen fertiliser application rate (kg ha^{-1})		Number of harvests
		Medium	High	
IB 0024	1982	200	400	7
IB 0027	1984	160	320	5
IB 0027	1985	160	320	5

analysis each experimental field was uniformly fertilised with potassium and phosphate according to recommendations (cf. [3]). During the growth period there were either five or seven harvests (Table 3) in each of which dry weights and nitrogen contents of potato tops and tubers were determined; the methods were the same as for experiments IB-0014. Detailed measurements of soil mineral nitrogen were also made; nitrate and ammonium were extracted from soil with 1 *M* NaCL and determined with a Technicon Autoanalyser [23]. Plot size was 6×4.5 m² and there were three replicates.

2.3.2. Time of emergence

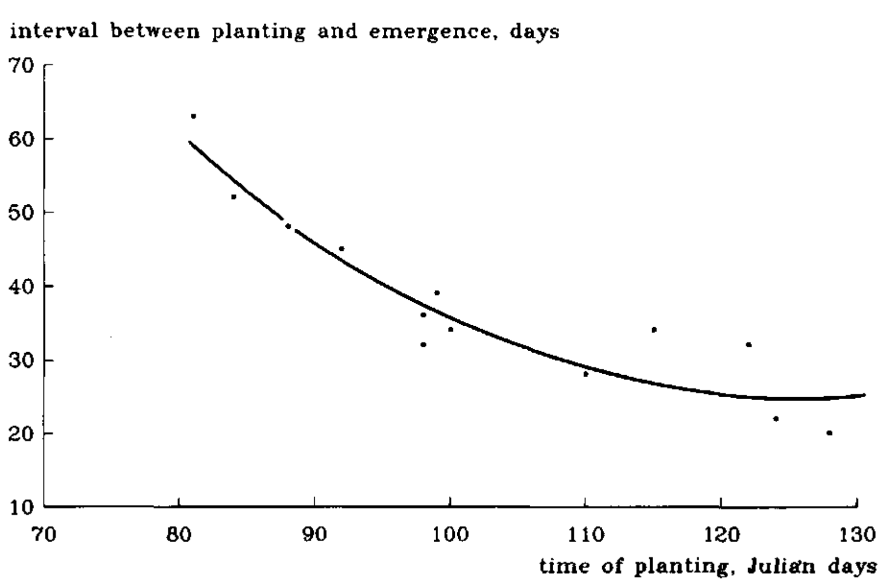
With the exception of the two 1976 experiments in the IB-0014 experiments the time of emergence of the potato crop could be derived from field records. There appeared to be a distinct negative relationship ($r^2 = 0.88$) between the date of planting and the interval between planting and emergence (Figure 1). It is defined by

$$T_E - T_P = 295 - 4.32\,T_P + 0.0172\,T_P^2 \qquad (9)$$

where T_E is time of emergence (Julian days), and T_P is time of planting (Julian days). T_E can thus be calculated as

$$T_E = 295 - 3.32\,T_P + 0.0172\,T_P^2 \qquad (10)$$

Figure 1: Relationship between Julian date of planting and the interval between planting and emergence. Thirteen IB-0014 experiments.



T_E is set equal to Julian day 139 when $T_P < 80$ Julian days and to Julian day 154 when $T_P > 130$ Julian days.

2.3.3. Recovery of nitrogen fertiliser

The recovery of nitrogen fertiliser, Rec, at any time during the growth period can be calculated as:

$$Rec = (N_{C+N} - N_{CON}) / N_F \tag{11}$$

where N_{C+N} and N_{CON} are the amounts of nitrogen in the entire crop (kg ha^{-1}) with and without nitrogen fertiliser, and N_F is amount of nitrogen fertiliser applied (kg ha^{-1}). In Table 4 the recovery of the medium and high nitrogen fertiliser application rates of the IB-0024/0027 experiments is shown at four intervals during the growth period. From Table 4 it can be seen that the recovery of nitrogen fertiliser depends on the level of fertiliser applied: the higher the level of fertiliser, the lower the recovery. Table 4 also shows that the recovery changed little in the course of time.

We found that Rec for vegetable crops declines linearly with an increase in N_F and with an increase in P_W, the actual %N in total dry matter. To correct for these effects of

Table 4: Recovery of nitrogen fertiliser in the IB-0024/0027 experiments. Recovery is calculated from Equation (11).

	Recovery			Average
	Experiment			
	0024 (1982)	0027 (1984)	0027 (1985)	
Medium level of nitrogen fertiliser*				
Harvest number				
2	0.69	0.65	0.47	0.60
3	0.49	0.68	0.52	0.55
4	0.51	0.71	0.57	0.60
5	0.57	0.68	0.54	0.60
Average	0.57	0.68	0.52	0.59
High level of nitrogen fertiliser**				
Harvest number				
2	0.42	0.57	0.38	0.46
3	0.34	0.52	0.45	0.44
4	0.42	0.52	0.53	0.49
5	0.53	0.49	0.40	0.47
Average	0.43	0.52	0.44	0.47

* 200 and 160 kg ha^{-1} for IB 0024 and IB 0027, respectively
** 400 and 320 kg ha^{-1} for IB 0024 and IB 0027, respectively

Table 5: Ratio of actual % N in dry weight of the entire crop, P_W, to the minimum % N needed for maximum growth, P_M, in the IB-0024/0027 experiments.

	P_W / P_M			Average
	Experiment			
	0024 (1982)	0027 (1984)	0027 (1985)	
Medium level of nitrogen fertiliser*				
Harvest number				
2	1.19	0.97	0.91	1.02
3	1.25	0.97	0.84	1.02
4	1.18	0.96	0.82	0.99
5	1.17	0.92	0.75	0.95
Average	1.20	0.94	0.83	1.00
High level of nitrogen fertiliser**				
Harvest number				
2	1.18	1.27	1.06	1.15
3	1.22	1.15	1.15	1.17
4	1.36	1.13	1.15	1.20
5	1.40	1.05	0.84	1.10
Average	1.29	1.15	1.05	1.16

* 200 and 160 kg ha^{-1} for IB 0024 and IB 0027, respectively

** 400 and 320 kg ha^{-1} for IB 0024 and IB 0027, respectively

Table 6: Ratio of total dry weight without application of nitrogen fertiliser, W_{ON}, to total dry weight with optimum application rate of nitrogen fertiliser, W_{Nop}. Experiments IB-0024/0027.

	W_{ON} / W_{Nop}			Average
	Experiment			
	0024 (1982)	0027 (1984)	0027 (1985)	
Harvest number				
2	0.78	0.66	0.78	0.74
3	0.94	0.70	0.84	0.83
4	1.03	0.70	0.77	0.83
5	1.03	0.81	0.75	0.86
Average	0.94	0.72	0.78	0.82

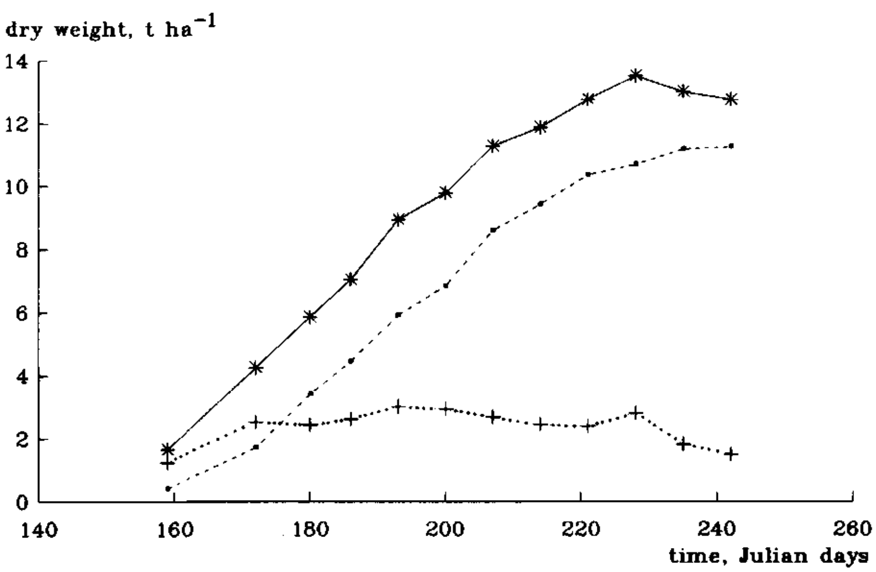
nitrogen nutrition we used results of the IB-0024/0027 experiments. The average value of P_W / P_M at the medium level of nitrogen fertiliser application was 1.00 and that at the high level 1.16 (Table 5). The average value of P_W / P_M without application of nitrogen fertiliser was considered to be approximately equal to the ratio of the total dry weight of plant mass when nitrogen fertiliser was withheld, W_{ON}, to that with the optimum level of nitrogen fertiliser, W_{NOp}, the ratio being 0.82 (Table 6). The average recoveries with the medium and high levels of nitrogen fertiliser application were 0.59 and 0.47, respectively (Table 4). From these measurements the average recovery from an infinitely small application rate of nitrogen fertiliser was estimated to be about 0.80. In the model the recovery is calculated according to the relationship between the average values of P_W / P_M and the foregoing average recoveries at the three levels of nitrogen fertiliser. The relationship is

$$Rec = 1.75 - 1.20\,(P_W / P_M) \qquad (12)$$

2.3.4. Maximum dry weight of foliage plus tubers

In order to calculate the growth rate coefficient K_2 (Equation (1), section 2.1.1.) the maximum dry weight of foliage plus tubers, W_{MAX}, must be known. However, in the 61

Figure 2: Example of the course of dry matter production in a potato crop. Experiment IB-0014 (1971), nitrogen fertiliser application rate 240 kg ha^{-1}. - - - - - tubers; . . . . . foliage; ______ foliage plus tubers.



experiments which will be used to test the model (section 3), only the tuber dry weight at final harvest is measured and not W_{MAX}. Moreover, use of the model by farmers or their technical advisors requires them to give the expected maximum yield as an input parameter. Potato growers are able to give a good estimate of maximum tuber yield, but not of W_{MAX}.

Figure 2, which gives an example of the increase in dry weight during the growth period, shows that total dry weight at final harvest can be smaller than it was earlier in the growth period. Most probably leaf drop is responsible for the decrease in total dry weight between W_{MAX} and final harvest. In Figure 3 final tuber dry weight is plotted against W_{MAX} for all three nitrogen fertiliser levels (no nitrogen fertiliser, a medium and a high rate of nitrogen fertiliser application) of the IB-0014 experiments. The data fitted a good ($r^2 = 0.92$) proportional linear relationship:

$$W_{MAX} = 1.165\ W_{FT} \qquad (13)$$

where W_{MAX} is maximum dry weight of foliage plus tubers (t ha^{-1}), and W_{FT} is final tuber dry weight (t ha^{-1}).

Figure 3: Relationship between tuber dry weight at final harvest, W_{FT}, and dry weight of foliage plus tubers at the time when it was maximum, W_{MAX}. IB-0014 experiments, all nitrogen fertilser levels.

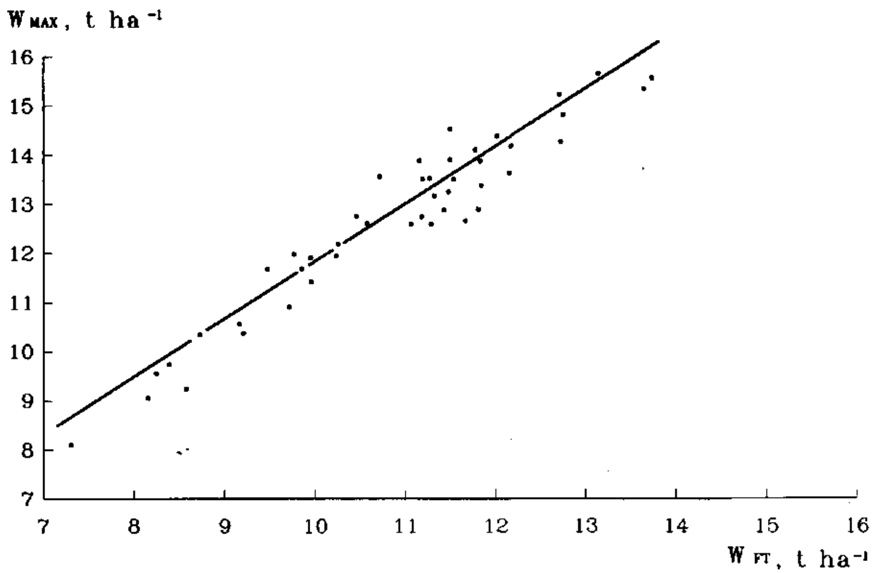
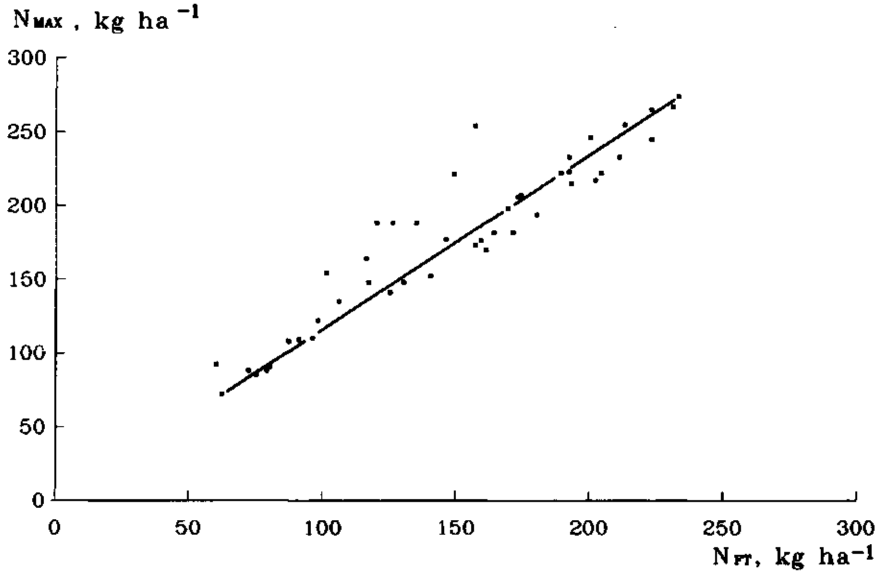


Figure 4: Relationship between amount of nitrogen in tubers at final harvest N_{FT}, and amount of nitrogen in foliage plus tubers at the time when it was maximum, N_{MAX}. IB-0014 experiments, all nitrogen fertiliser levels.



2.3.5. Maximum amount of nitrogen in foliage plus tubers

Some means was needed of providing an estimate of the amount of nitrogen in the entire crop in each of the 61 experiments to provide further tests of the validity of the model (see section 3). The amount of nitrogen in the tubers at the final harvest, N_{FT}, was determined for all three nitrogen fertiliser levels of the IB-0014 experiments. It was found to be related to N_{MAX}, the amount of nitrogen in the entire crop at the time when it was maximum (Figure 4). A good ($r^2 = 0.88$) proportional linear relationship fitted the data:

$$N_{MAX} = 1.188\ N_{FT} \qquad (14)$$

with N_{MAX} and N_{FT} in kg ha^{-1}.

3. MODEL PREDICTIONS

The relationships mentioned in section 2 have been combined into a dynamic model for calculating the response of potatoes to nitrogen fertiliser throughout the growth period. The model is used to predict tuber yields and the optimum level of nitrogen fertiliser for each of 61 different field experiments. The 61 experiments were entirely independent of those used for developing the relationships from which the model was derived.

First, tuber yields will be predicted from separate input data for each experiment to test the validity of the model. For instance, in this test the weather records obtained during each experiment were used as inputs into the model. Next, the model will be used to predict yields and nitrogen fertiliser optima with only the input data that are available shortly before application of nitrogen fertiliser. In this case we use the best estimate of future weather (standard weather) as an input into the model because at the time of planting the future weather is not known.

No attention will be paid to the nitrogen content in the tubers at final harvest, because the difference between predicted and measured values was very small (cf. [15]).

3.1. Experiments

The model was tested against the results of 61 nitrogen fertiliser experiments with potatoes. There were altogether 99 experiments, but those where maximum fresh tuber yields were less than 50 t ha^{-1} were excluded to reduce the volume of work. The experiments were carried out on various soil types during the period 1973-1982 (Table 7). In each experiment there were seven rates of nitrogen fertiliser: 0, 100, 150, 200, 250, 300 and 400 kg ha^{-1}. Nitrogen fertiliser was applied as ammonium nitrate limestone as a single dressing before planting. After soil analysis each experimental field was uniformly

Table 7: Field experiments used for testing the model. Distribution of the experiments over the years and soil types.

Year	Number of experiments			Total
	Soil type			
	Sand	Loam	Clay	
1973		1		1
1974	1	2		3
1975		1		1
1976		1	1	2
1977	1	3	1	5
1978	1	4	1	6
1979		3	1	4
1980	6	7	2	15
1981	5	8	4	17
1982	3	4		7
Total	17	34	10	61

fertilised with potassium and phosphate according to current Dutch recommendations (cf. [3]). In the experiments soil mineral nitrogen was measured at the onset of spring using the same analytical method as has been described in section 2.3.1. At final harvest fresh and dry tuber yield and the nitrogen content ("salicylate-method" [28]) of the tubers were measured. Further experimental details are given elsewhere [22])

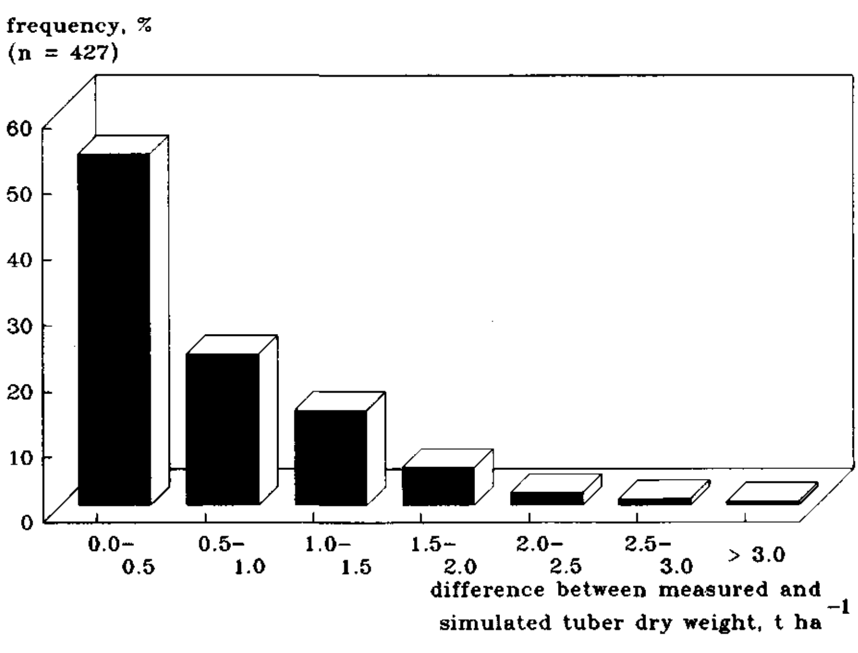
3.2. Prediction of tuber yield with separate input data for each experiment

Tuber yield at final harvest is predicted from the input data corresponding to each experiment.

The field-dependent inputs to the model are:

* actual amount of soil mineral nitrogen in early spring (measured for each experiment)
* actual time and rate of nitrogen fertiliser application
* actual time of planting

Figure 5: Difference between measured and simulated tuber dry weight. Simulations were done with actual input data for seven rates of nitrogen fertiliser applied in 61 experiments.



* maximum tuber dry weight as measured in the experiment
* soil type (for sand, loam and clay the moisture contents at field capacity are considered to be 0.30, 0.40, and 0.50 ml water per ml soil, respectively).
* actual daily values of soil temperature at 10 cm depth and precipitation surplus for each experiment.

For all experiments the rate of apparent nitrogen mineralisation was assumed to be 1 kg ha^{-1} d^{-1} at 12°C. The maximum rooting depth, which was not measured in the experiments, was considered to be 60 cm for all experiments. With one exception (when the harvest was early) the actual date of harvest varied between 9 September and 25 October and almost certainly did not correspond to the date of cessation of growth. In the model it is assumed that growth always ceased on 1 September and that tuber dry weight did not change from this date onwards. Weather data were derived from KNMI reports [1, 2].

Tuber dry weight at final harvest is predicted for each of the seven rates of nitrogen fertiliser in the 61 experiments. Thus a total of $7 \times 61 = 427$ simulations were performed. The frequency distribution of the differences between measured and simulated tuber dry weights at final harvest is presented in Figure 5. In 53% of the simulations the difference was less than 0.5 t ha^{-1} and in 76% it was less than 1 t ha^{-1}. The results appear to be quite satisfactory, because the measured tuber dry weight averaged 12.6 ha^{-1} ($n = 427$), so that 0.5 and 1.0 t ha^{-1} correspond to deviations from the average yield of 4 and 8%, respectively.

The main difficulty in assessing the validity of any simulation model is to determine to what extent the differences between model and experiment result from errors in measurement and to what extent they result from a weakness in the model itself. Sutherland *et al.* [25] developed a method to overcome this problem. It was used to assess the validity of the model for predicting tuber dry weight. The difference between measured and simulated tuber dry weight is calculated for each level of nitrogen fertiliser of each experiment. $\sqrt{\sigma_E^2}$ is estimated from the residual sums of squares of the untransformed data after taking account of the main effect of fertiliser level. Any bias significantly greater than 5% of the true mean at the 5% probability level is considered to indicate a weakness in the model. A summary of the biases obtained with the model is given in Table 8; the data point in each experiment corresponding to the maximum tuber dry weight is omitted as it was used as an input for the simulations. The extent to which the biases are related to the level of nitrogen fertiliser has been tested with a rank correlation test, which compares the ranks of the biases with ranks of the levels of nitrogen fertiliser (Table 8). When the biases increase (or become less negative) with increasing level of nitrogen fertiliser, the values of rank correlation are near +1, and when the biases decrease (or become more negative) with increasing level of fertiliser the values of rank correlation are near −1.

In table 8 it is clear that the model predicted tuber dry weights well, especially at the higher levels of nitrogen fertiliser. At the lower levels of nitrogen fertiliser, however, tuber dry weight was underestimated in several experiments (expts 9, 16, 22, 40, 43, 44, 46, 49, 52, 60 and 61), whereas it was overestimated in three experiments (expts 20, 21, 29). Table 8 shows that in seven experiments the rank correlation coefficient had a value of −1, indicating that the biases decreased systematically with increasing level of nitrogen fertiliser. Obviously, the agreement between prediction and experiment at the higher nitrogen fertiliser levels can at least partly be explained by the fact that the maximum tuber dry weight of each experiment was used as an input to the model. Maximum tuber dry weights were mostly obtained at one of the higher nitrogen fertiliser levels (see also the second column of Table 8).

Table 8: Test of the validity of the model for calculating tuber dry weight at final harvest. d is the bias (difference between prediction and measurement). For each experiment the number of biases for comparison is six.

Experiment	N level[a] omitted[b]	Significant biases				Spearman rank correlation coefficient[d]
		d < −5% mean		d > +5% mean		
		no.	ranks[c]	no.	ranks[c]	
1	4	0		0		0.20
2	7	0		0		0.46
3	5	0		0		0.03
4	4	0		0		−1.00**
5	5	0		0		−0.66
6	7	0		0		−0.83
7	3	0		0		−0.37
8	6	0		0		0.03
9	5	1	1	0		−0.83
10	2	0		0		−0.94*
11	3	0		0		−0.60
12	3	0		0		−0.94*
13	7	0		0		0.89*
14	6	0		0		−0.54
15	6	0		0		−0.26
16	3	1	1	0		−0.83
17	3	0		0		−0.66
18	2	0		0		−0.20
19	6	0		0		0.09
20	7	0		2	1,2	0.83
21	4	0		1	1	0.20
22	5	1	2	0		−0.94*
23	5	0		0		−0.09
24	6	0		0		0.03
25	2	0		0		−0.14
26	5	0		0		−0.94*
27	6	0		0		−1.00**
28	3	0		0		−0.71
29	6	0		1	1	0.83
30	2	0		0		−0.71
31	5	0		0		0.60
32	2	0		0		−0.94*
33	6	0		0		+0.94*
34	5	0		0		−0.63
35	4	0		0		−0.37
36	2	0		0		−0.09
37	6	0		0		0.20
38	3	0		0		−0.60
39	5	0		0		−0.77
40	3	1	1	1	6	−0.94*
41	5	0		0		−0.66
42	5	0		0		−0.49
43	5	3	1,2,3	0		−1.00**

44	5	1	1	0		−0.94*
45	4	0		0		−1.00**
46	2	2	1,2	0		−0.94*
47	6	0		0		−0.94*
48	4	0		0		−0.94*
49	4	1	1	0		−0.83
50	4	0		0		−0.89*
51	7	0		0		−0.66
52	7	1	1	0		−1.00**
53	3	0		0		−0.54
54	6	0		0		0.31
55	3	0		0		0.26
56	5	0		0		−1.00**
57	6	0		0		−0.89*
58	6	0		0		−1.00**
59	6	0		0		−0.89*
60	5	2	2,3	0		−0.26
61	2	1	1	0		−0.94*

[a] 1, 2, 3, 4, 5, 6, and 7 correspond to 0, 100, 150, 200, 250, 300, and 400 kg fertiliser nitrogen per ha, respectively

[b] The level with maximum recorded tuber dry weight is omitted

[c] The number refer to the levels of fertiliser nitrogen, see [a]

[d] Rank correlations marked * or ** are significantly different from 0 at the 5% or 1% level, respectively.

**Table 9: Average maximum tuber dry weights in the 61 experiments.
( ) Number of experiments.**

Area	Maximum tuber dry weight, t ha^{-1}			Average
	Soil type			
	Sand	Loam	Clay	
North	12.8 (4)	12.4 (3)	12.1 (1)	12.5 (8)
Rivers	–	13.0 (2)	14.6 (1)	13.5 (3)
South	13.6 (10)	13.4 (8)	–	13.5 (18)
West	–	13.3 (10)	15.4 (1)	13.5 (11)
Central	12.9 (3)	14.2 (2)	14.1 (6)	13.8 (11)
Southwest	–	14.4 (9)	12.0 (1)	14.2 (10)
Average	13.3 (17)	13.6 (34)	13.9 (10)	13.5 (61)

The results presented here are better than those with winter wheat [17, 25]. Despite discrepancies at lower levels of nitrogen fertiliser, the model, with values for inputs specific for each experiment, appears to predict tuber dry weight very well. The component equations seem thus to be sound. The validity of the model, if used with the inputs likely to be available for advisory purposes, is evaluated in the next section.

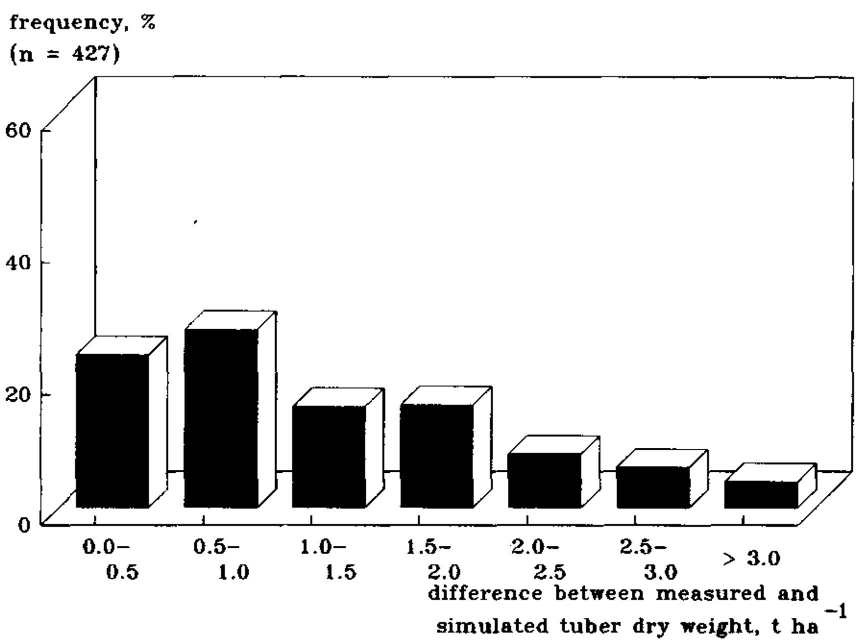
3.3. Prediction of optimum nitrogen fertiliser application rate with standard input data

Final tuber dry weight at each of the seven nitrogen fertiliser levels of the 61 experiments is predicted from input data that are available at the onset of spring. Next, for each experiment a response curve is fitted to the predicted tuber weights by the method of Neeteson and Wadman (1987). From each response curve the optimum application rate of nitrogen fertiliser is calculated.

The field dependent inputs to the model are:

* actual amount of soil mineral nitrogen in early spring (measured at each experiment)
* expected time of nitrogen fertiliser application
* expected time of planting
* expected maximum tuber dry weight
* soil type
* standard daily values of soil temperature at 10 cm depth and precipitation surplus.

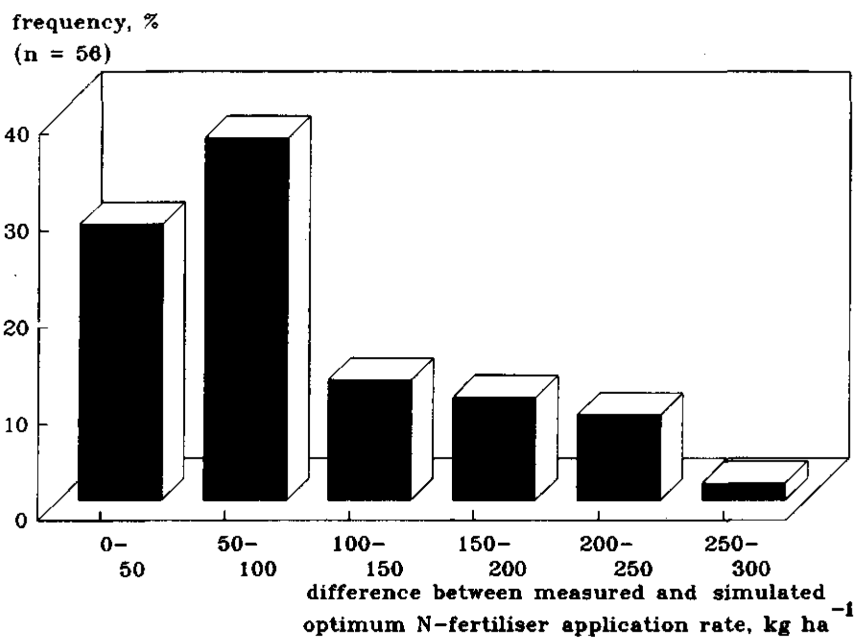
Figure 6: Difference between measured and simulated tuber dry weight. Simulations were done with standard input data for seven rates of nitrogen fertiliser applied in 61 experiments.



The simulations were performed with actual dates of nitrogen fertiliser application and planting on the assumption that farmers or their technical advisers are able to give a good estimation of these dates at the time the model is to be used for practical purposes, i.e. just before nitrogen fertiliser application. Based on previous records of maximum tuber dry weights per area (Table 9), it was assumed that the expected maximum tuber dry weight in the northern part of the Netherlands is 12.5 t ha^{-1}. In the central and southwestern part it was assumed to be 14 t ha^{-1}, and in other areas 13.5 t ha^{-1} (Table 9). As in section 3.2., the moisture content at field capacity was considered to be 0.30, 0.40, and 0.50 ml water per ml soil for the sandy, loamy, and clayey soils, respectively. Standard weather data were derived from the past 30-years' data in weather reports ([1, 2]).

As in the tests using separate input data for each experiment (section 3.2.), the rate of apparent nitrogen mineralisation was assumed to be 1 kg ha^{-1} d^{-1} at 12°C in each experi-

Figure 7: Difference between measured and simulated optimum application rates of nitrogen fertiliser. The simulations were done with standard input data.



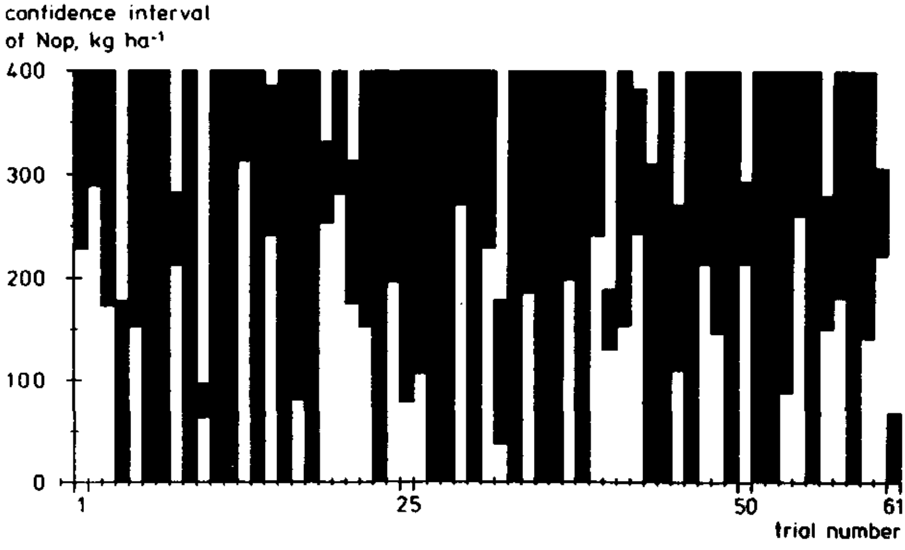
ment and the maximum rooting depth 60 cm. It was also assumed that growth ceases on 1 September.

The frequency distribution of the differences between measured and simulated tuber dry weights at final harvest is presented in Figure 6. Obviously, the differences shown in Figure 6 are larger than those of Figure 5, owing to the use of 'standard' maximum dry tuber weights instead of those measured at each site. Further cause of discrepancy is introduced by using 'standard' rather than 'real' weather data. Nevertheless 80% of all predicted yields were within 2 t ha^{-1} of those measured, and as 2 t ha^{-1} corresponds to 16% of the 'average' yield, this means that 80% of the predictions did not deviate from the mean by more than 16%.

Nitrogen fertiliser response curves were fitted to the predicted tuber dry weights and optima were calculated as described earlier [22] by assuming that the ratio of the cost of 1 kg nitrogen fertiliser to the price of 1 tonne dry tuber weight is 0.0016. In other work with fresh tuber weights [22] a ratio of 0.0075 was used, the prices being 1 kg fertiliser = DFL 1.50 and 1 tonne tubers = DFL 200. The average measured dry-matter content of the tubers at final harvest (at optimum application of nitrogen fertiliser) was 21.3%, which implies that the price of 1 tonne dry tuber weight equals DFL 939 and that the monetary ratio is 0.0016.

In figure 7 the frequency distribution of the difference between measured and simulated optimum application rates of nitrogen fertiliser is presented. In this figure results of

Figure 8: Confidence intervals (black bars) of the optimum application rates of nitrogen fertiliser (Nop) as measured in the 61 experiments. Only those parts of the confidence intervals are shown which lay within the range of applied nitrogen fertiliser: 0-400 kg ha⁻¹. Price ratio = 0.0016.



5 experiments are not included, because the measured optima lay outside the range of tested levels of nitrogen fertiliser. The deviation of the predicted optimum from the measured optimum was less than 50 kg nitrogen per ha in 29% of the experiments. It was less than 100 kg nitrogen per ha in 66% of the experiments. At first sight, this outcome suggests the model is not satisfactory for giving nitrogen fertiliser recommendations.

One way of testing the effectiveness of the model for advisory purposes is to check whether the predicted optimum application rates of nitrogen fertiliser fall within the confidence limits for the measured optimum rates. The confidence intervals for the measured optima of the 61 experiments are shown in Figure 8. In Figure 8 only those parts of the confidence intervals are indicated that lay within the range of tested levels of nitrogen fertiliser, viz., 0-400 kg ha^{-1}. The predicted optima for 49 experiments, i.e. 80%, fell within the confidence limits for the measured optima. Most of the large differences between predicted and measured optima (Figure 7) were not statistically significant and so the comparisons gave little information about the reliability of the model. Sylvester-Bradley *et al.* [26], Sutherland *et al.* [25]), and Neeteson and Wadman [20] found that the error in determining measured optimum application rates of nitrogen fertiliser is generally very large. Therefore there can be little doubt that comparing predicted and measured optima is a poor way to test any model. Due to the wideness of the confidence intervals even poor models will show promising results. We prefer to test the validity of the model by determining to what extent yield losses occur if the predicted optimum application rate of nitrogen fertiliser had been applied.

In Figure 9 the frequency distribution of the tuber dry weight deficits, i.e. the deviations from the tuber dry weights obtained with the measured optimum application rate in each individual experiment, is shown if the optima as predicted by the model had been applied. The tuber dry weight deficit had a negative value when tuber yield with the predicted optimum was higher than the measured optimum; it had a positive value when tuber yield with the predicted optimum was lower than with the measured optimum. In 68% and 16% of the experiments the tuber dry weight deficit was less than 1% and between 1 and 2%, respectively, which means that the probability of getting significant yield depressions is very small when the model is used for the assessment of the application rate of nitrogen fertiliser. The conclusion is that the model is reasonably sound and that it may be used as a tool to predict the optimum application rate of nitrogen fertiliser for potatoes.

We next consider how the model compares with other methods of predicting the optimum application rate of nitrogen fertiliser. The simplest advice is to recommend the same level at all sites, irrespective of differences in fields and husbandry practices [8, 9, 20]. Table 10 shows the probability distribution of tuber dry weight deficits if the 61 experiments had been fertilised with various fixed rates of nitrogen fertiliser. From this table it is clear that the probability of getting serious yield depressions was high with either 0 or 100 kg nitrogen fertiliser per hectare applied to all sites. However, a fixed rate of 300 kg ha^{-1} almost always gave near maximum yields; the probability of getting tuber dry weight deficits of less than 2% was 84% and deficits of less than 5% was 95%. These figures are very similar to those obtained with the model (Table 10). With the model the average recommended rate of nitrogen fertiliser in the 61 experiments was 286 kg ha^{-1} which is 14 kg ha^{-1} less than with a fixed rate. It is notable that the effectiveness of the current method of nitrogen fertiliser recommendation for potatoes in the Netherlands, i.e. the N_{min}-method, gives about the same yield deficit as the best fixed rate, but with about 40 kg less nitrogen fertiliser per hectare [20].

Figure 9: The shortfall in tuber yield obtained with the optimum level of nitrogen fertiliser predicted with the model, expressed as a percentage of the yield obtained with the measured optimum level of nitrogen fertiliser in the 61 experiments.

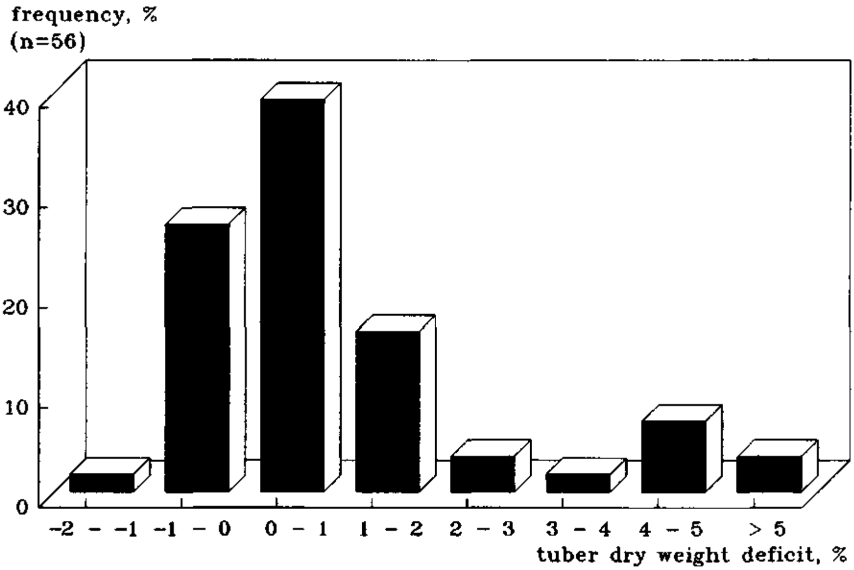


Table 10: Probability distribution of tuber dry weight deficits with the optimum predicted in the model for each site and with a fixed rate of nitrogen fertiliser for all sites. 61 Experiments.

Tuber dry weight deficit, % of tuber dry weight obtained with measured optimum application rate of fertiliser	Model	Probability, %				
		N-fertiliser recommendation				
		Fixed rate of N fertiliser, kg ha^{-1}				
		0	100	200	300	400
<-1	2	0	0	0	4	7
< 0	29	0	5	12	30	12
< 1	68	2	23	59	64	21
< 2	84	2	30	70	84	43
< 3	88	4	41	77	88	52
< 4	89	5	50	86	91	62
< 5	96	9	57	88	95	62

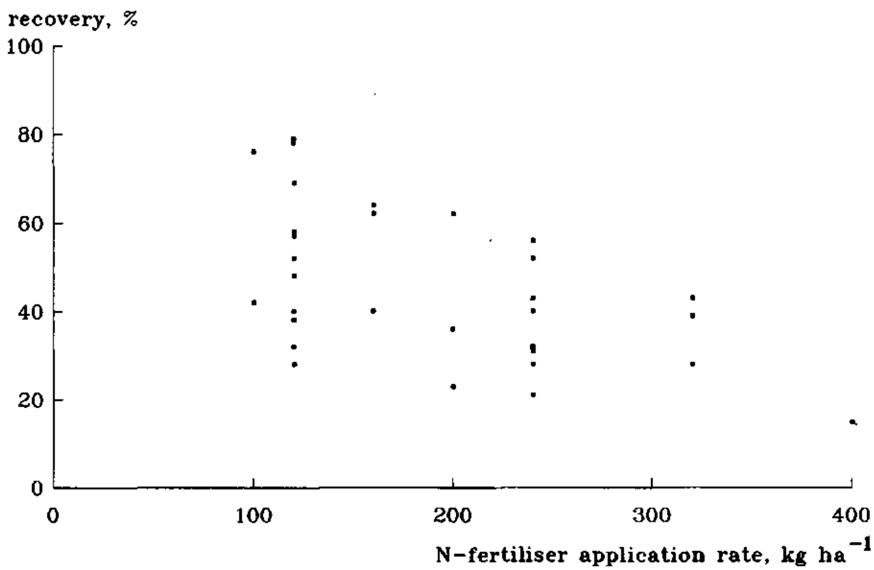
4. CONCLUDING REMARKS

4.1. Conclusions

The dynamic model presented here described response of potatoes to nitrogen fertiliser quite well. With few exceptions tuber dry weight for each of seven nitrogen fertiliser levels in 61 experiments were predicted accurately with separate input data for each experiment. The inputs to the model are readily available, so the model could, if necessary, be used for advisory purposes. With standard input data the optimum nitrogen fertiliser application rate was predicted for 61 experiments. Although predicted optima on occasion differed considerably from measured optima, these discrepancies could be largely attributed to the considerable error in the measured optima. If the predicted optimum application rates of nitrogen fertiliser had been applied to the 61 experiments, the yield deficits from the yields obtained with the measured optima were less than 2% in 84% of the experiments.

In spite of these promising results we hesitate to put the current version of the model into practice until after we have improved the treatment of recovery and nitrogen mineralisation (see next section). In contrast to most current methods of recommenda-

Figure 10: Recovery of nitrogen fertiliser at final harvest of the IB-0014 and IB-0024/0027 experiments.



tion the model may also be useful for making decisions about splitting nitrogen fertiliser applications into more than one dressing, because the model calculates the nitrogen status of the crop and the soil each day during the growth period. As most relationships which underly the model seem to be widely applicable, the model may be used for other crops after minor modifications [16].

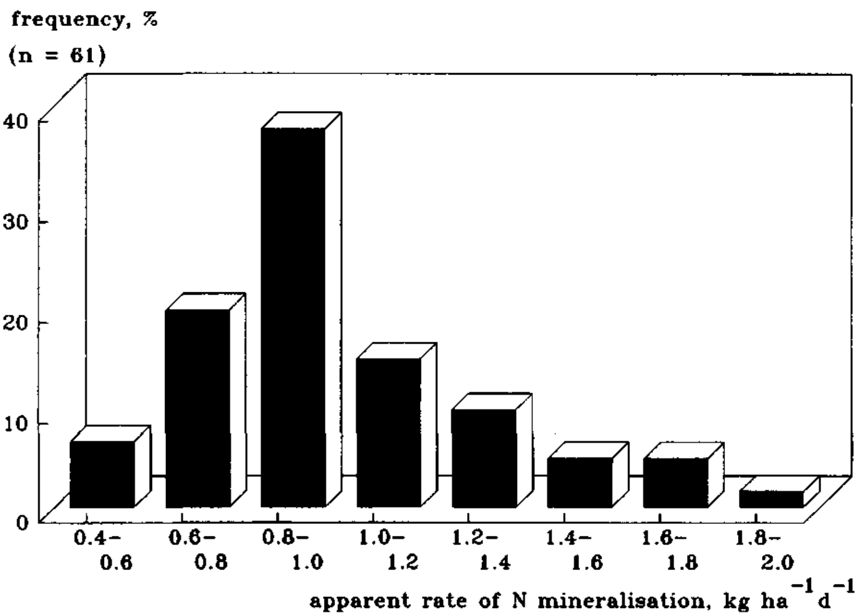
4.2. Possibilities for improving the model

The main possibilities for improvement appear to lie in better treatment of the recovery of fertiliser nitrogen by the crop and the mineralisation of nitrogen.

It is clear that the recovery of nitrogen fertiliser decreases with increasing level of nitrogen fertiliser, but there also appears to be a very large variation between years (Fig. 10). To take account of both effects in the model, recovery is related to the nitrogen status of the crop, but we feel this treatment needs refinement.

In the model, the rate of apparent nitrogen mineralisation is fixed at 1 kg ha^{-1} d^{-1}, which

Figure 11: Apparent rates of nitrogen mineralisation in the 61 experiments.



corresponds to the rate of mineralisation at 12°C. From data on soil mineral nitrogen in early spring and at the time of final harvest without nitrogen fertiliser, nitrogen uptake by the crop without nitrogen fertiliser, and the amount of nitrate leached to below rooting depth during the growth period (estimated by Burns' model [7]) we have calculated the apparent mineralisation rate in each of the 61 experiments (Fig. 11). It ranged from 0.4 to 2.0 kg ha^{-1} d^{-1} (Fig. 11) with an average of 1 kg ha^{-1} d^{-1}. More needs to be known about the reasons for this variation. On the basis of field histories (cropping sequence, application of organic manures) it should be possible to differentiate between rates of nitrogen mineralisation in the various fields and thus to provide inputs to the model that take better account of inter-site variation in mineralisation rate.

Further improvements would be to include the reduction of growth of the potato crop due to lack of water and to give more consideration to root growth.

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APPENDIX

Symbols used and their definitions

Symbol	Definition
E_C	Transpiration from crop canopy (mm)
E_O	Evaporation from an open water surface (mm)
E_S	Evaporation from bare soil (mm)
E_T	Evapotranspiration from bare soil plus crop (mm)
f_r	Fraction of the soil surface covered by the crop
F_R	Coefficient for the fraction of available soil mineral nitrogen that can be absorbed by roots
G_F	Growth rate factor to correct for growth being reduced by sub-optimum %N in the total dry matter
K_1	Coefficient in Equation (1); set equal to 1 t ha^{-1}
K_2	Coefficient in Equation (1) (t ha^{-1} d^{-1})
m	Constant rate of apparent nitrogen mineralisation throughout the growth period (kg ha^{-1} d^{-1})
M_N	Soil mineral nitrogen plus amount of nitrogen in the crop (kg ha^{-1})
N_{cON}	Amount of nitrogen in foliage plus tubers without nitrogen fertiliser (kg ha^{-1})
N_{c+N}	Amount of nitrogen in foliage plus tubers with nitrogen fertiliser (kg ha^{-1})
N_F	Nitrogen fertiliser application rate (kg ha^{-1})
N_{FT}	Amount of nitrogen in tubers at final harvest (kg ha^{-1})
N_{MAX}	Maximum amount of nitrogen in foliage plus tubers (kg ha^{-1})
N_{min}	Amount of soil mineral nitrogen (kg ha^{-1})
P_M	Minimum %N in total dry matter needed for maximum growth rate
P_O	%N in total dry matter when growth ceases
P_W	Actual %N in total dry matter
Q	Coefficient for the decline in mineralisation rate with depth down the soil profile (cm^{-1})
R	Ratio of the dry weight of foliage to that of foliage plus tubers
R_U	Ratio of the amount of nitrogen in foliage to that in foliage plus tubers
Rec	Recovery of nitrogen fertiliser
T	Time (d or Julian days)
T_E	Time of emergence (Julian days)
W	Total weight of dry matter (t ha^{-1})
W_{FT}	Tuber dry weight at final harvest (t ha^{-1})
W_{MAX}	Maximum dry weight of foliage plus tubers (t ha^{-1})
W_{ON}	Dry weight of foliage plus tubers without application of nitrogen fertiliser t ha^{-1})
W_{Nop}	Dry weight of foliage plus tubers with optimum application of nitrogen fertiliser

Chapter 7

Model calculations of nitrate leaching during the growth period of potatoes

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Model calculations of nitrate leaching during the growth period of potatoes

J. J. NEETESON[1], D. J. GREENWOOD[2] & A. DRAYCOTT[2]

[1] Institute for Soil Fertility, P.O. Box 30003, NL 9750 RA Haren, Netherlands
[2] Institute of Horticultural Research, Wellesbourne, Warwick CV35 9EF, UK

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Abstract

To estimate the amount of nitrate lost due to leaching during the growth period of potatoes and the amount of mineral nitrogen present in the soil at harvest time, i.e. residual mineral nitrogen, calculations were performed with a previously derived simulation model for the response of potatoes to nitrogen. In the calculations those factors were varied that were considered to affect the amount of nitrate lost due to leaching: precipitation in spring and summer, soil type, mineralization rate of soil organic matter, and amount of fertilizer nitrogen applied. It was calculated that the total loss of nitrogen, i.e. the amounts leached in spring plus the amounts accumulated as residual soil mineral nitrogen, were similar in a loamy sand and a clay loam. The greater loss by leaching from the sand was offset by the greater accumulation of mineral nitrogen in the loam. Under normal conditions of precipitation and mineralization the total loss increased from about 20 kg N per ha at a fertilizer nitrogen application rate of 200 kg N per ha to about 190 kg N per ha at a rate of 400 kg N per ha. At a high rate of mineralization, an application as low as 100 kg fertilizer N per ha resulted in a total loss of about 60 kg N per ha. It was concluded that little nitrate leaching occurs when the current nitrogen fertilizer recommendations are followed, provided that mineralization in the soil proceeds at an average rate. When high mineralization rates are likely to occur, however, the recommendations should be lowered.

Keywords: fertilizer nitrogen, nitrate leaching, nitrogen mineralization, potatoes, residual soil mineral nitrogen, simulation model

Introduction

As there is generally a large interval between the time of application (usually in March) and the period of major uptake of nitrogen by the potatoes (June-July; Dyson & Watson, 1971), fertilizer nitrogen applied to this crop can be subject to leaching in spring. Since potatoes are rather inefficient users of nitrogen (Prins et al., 1988), nitrogen not taken up by the crop could also be leached in summer, or it could accumulate in the soil, and then be leached out of it in autumn and winter, when the soil is fallow and there is no crop to absorb nitrate.

However, reports of direct measurements of nitrate leaching during the growth of potatoes in field experiments could not be found, and data on accumulation of soil mineral nitrogen after potato cropping proved to be scarce (Prins et al., 1988). Since it is expensive to perform such field experiments, we attempted in this paper to predict nitrate leaching and accumulation of soil mineral nitrogen in a cheaper and less time-consuming way by means of dynamic simulation. For this purpose a slightly modified version of a previously derived model was used. It has predicted responses to nitrogen satisfactorily, not only for potatoes (Greenwood et al., 1985b; Neeteson et al., 1987), but also for various vegetable crops (Greenwood & Draycott, 1989).

In the calculations those factors were varied that were considered to have most effect on nitrate leaching, i.e. precipitation in spring and summer, soil type, mineralization rate of soil organic matter, and amount of fertilizer nitrogen applied.

Materials and methods

Model

The calculations were performed with the simulation model for the response of potatoes to nitrogen (Greenwood et al., 1985b; Neeteson et al., 1987), modified as described by Greenwood & Draycott (1989) to take account of the decline in apparent recovery of soil mineral nitrogen by the crop with increase in nitrogen status of the crop; apparent recovery varied by about 15 %. The model calculates on a daily basis potential and actual increase in total dry weight of the potato crop, potential and actual uptake of nitrogen by the crop, mineralization of soil organic matter, soil moisture content, redistribution of nitrate through the soil profile, and depth of rooting. The field-dependent inputs required by the model are amount of soil mineral nitrogen in early spring, time and rate of fertilizer nitrogen application, mineralization rate, time of planting of the potato tubers, maximum dry weight of tuber plus foliage, maximum depth of rooting, field capacity of the soil, daily values of soil temperature at 10 cm depth, daily values of precipitation surplus, and evaporation from an open water surface.

The potato crop is visualized as growing on soil that is divided into 5-cm-thick layers. From the expected maximum dry weight and the time between emergence and termination of crop growth, the model first calculates a growth rate coefficient for plants that are not subjected to any nitrogen stress. As the crop grows, the roots penetrate more and more of the 5-cm layers and are able to extract mineral nitrogen from them. The minimum concentration below which the roots are unable to absorb mineral nitrogen from a soil layer was considered to be 0.46 kg N per cm of soil, but all mineral nitrogen above that concentration was deemed available for uptake by the crop. The nitrogen demand of the crop depends on its dry weight. Actual uptake is less than demand when there is insufficient available mineral nitrogen in the soil. In that case the growth rate of the crop is restricted. It is assumed that all soil mineral nitrogen is in the form of nitrate, because in Dutch soils the rate of nitrification is generally much higher than the rate of mineralization. Moreover, fertilizer ammonium is usually nitrified within a few weeks after application. Mineralization of soil organic matter is assumed to proceed at a fixed rate which is only dependent on soil temperature. Mineralization is considered to take place almost entirely in the upper 30 cm of soil. Leaching of nitrate is described according to Burns (1974).

Model calculations

Model calculations were made for five application rates of fertilizer nitrogen, and combinations of amounts of precipitation in spring (March-May) and summer (June-August), two field capacities of the soil, and two rates of nitrogen mineralization (Table 1).

The various amounts of precipitation in spring and summer were chosen on the basis of the frequency distributions of the total amounts of precipitation in spring and summer as measured at the central meteorological station in the Netherlands during the period 1906-1988 (Fig. 1). For each period a normal and a wet year were chosen (Table 1). Precipitation in 1965, the year in which total precipitation in March-August was the largest for the period 1906-1988, was also included in the calculations. The daily rainfall in the three springs and three summers is shown in Figs. 2 and 3, respectively. The spring and summer precipitation inputs in the model are given in Table 2.

Table 1. Variable inputs in the model.

Parameter	Values
Precipitation March-May (mm)	188 (1939) 241 (1987) 272 (1965)
Precipitation June-August (mm)	227 (1972) 308 (1968) 353 (1965)
Field capacity of the soil ($cm\ cm^{-3}$)	0.27 (0-30 cm), 0.20 (30-90 cm) 0.33 (0-30 cm), 0.32 (30-90 cm)
Mineralization rate at 12 °C (kg N per ha per day)	1 2
Fertilizer nitrogen application rate (kg N per ha)	0 100 200 300 400

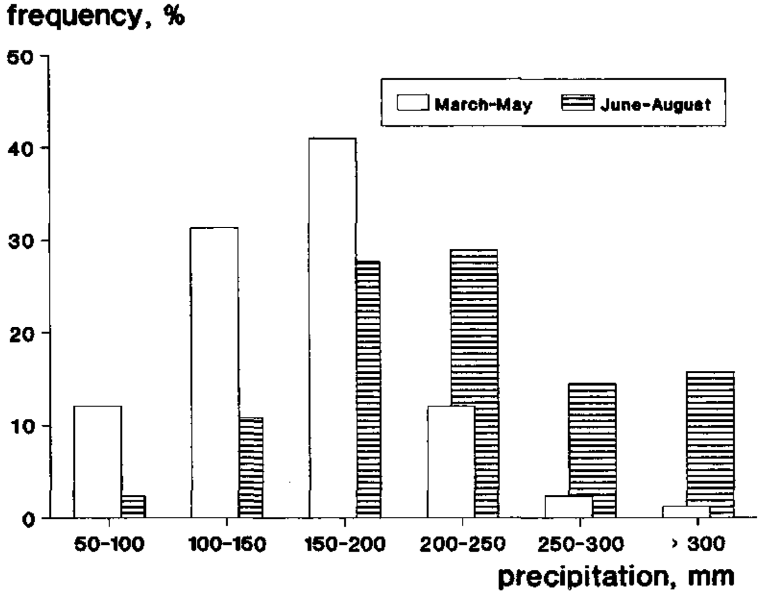

Fig. 1. Frequency distribution of cumulative precipitation in spring (March-May) and summer (June-August) at the central meteorological station in the period 1906-1988. Data derived from Anon. (1906-1988).

The field capacities of the soil were chosen as being representative of a loamy sand and a clay loam (Wösten et al., 1987).

The mineralization rates of 1.0 and 2.0 kg N per ha per day were chosen, because in field experiments with potatoes it was found earlier that these values corresponded to the average and maximum value of nitrogen mineralization (Neeteson et al., 1987).

The inputs of the model, having values that were identical for each calculation, are given in Table 3.

The data listed in Table 3 were chosen as being typical for potato culture in the Netherlands, as are those on amount of soil mineral nitrogen in early spring and the distribution over the soil layers, and dry weight of tubers planted (2 t fresh tubers per ha with a dry-matter content of 25 %).

The recovery of nitrogen by the tops plus the tubers at low nitrogen nutrition was set at 80 %, as was done in some previous studies (Greenwood et al., 1985b).

The maximum rooting depth of 60 cm and the maximum total dry weight of 17.5 t ha^{-1} were assumed to be representative of a high-yielding potato crop.

Long-term averages of the daily evaporation and soil temperature measurements at the central meteorological station (Anon., 1989) were used. Evaporation varied between 1.4 and 4.0 mm per day; soil temperature at 10 cm depth varied between 3.0 and 17.1 °C.

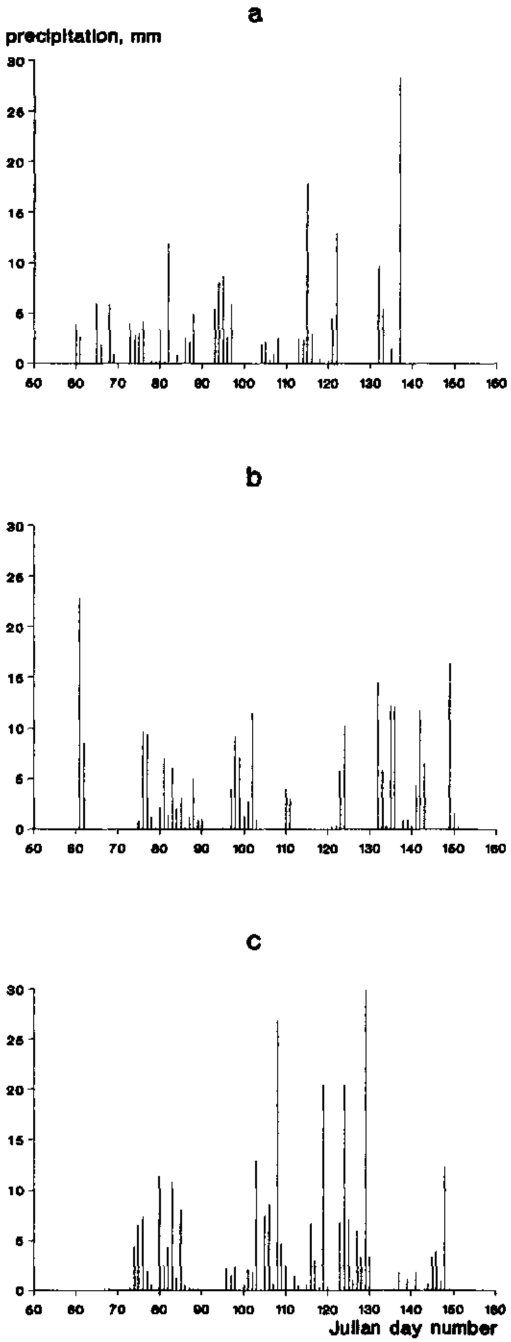

Fig. 2. Daily values of precipitation in spring (March-May = Julian day 60-Julian day 151) at the central meteorological station in 1939 (normal, a), 1987 (wet, b), and 1965 (extremely wet, c). Data derived from Anon. (1906-1988).

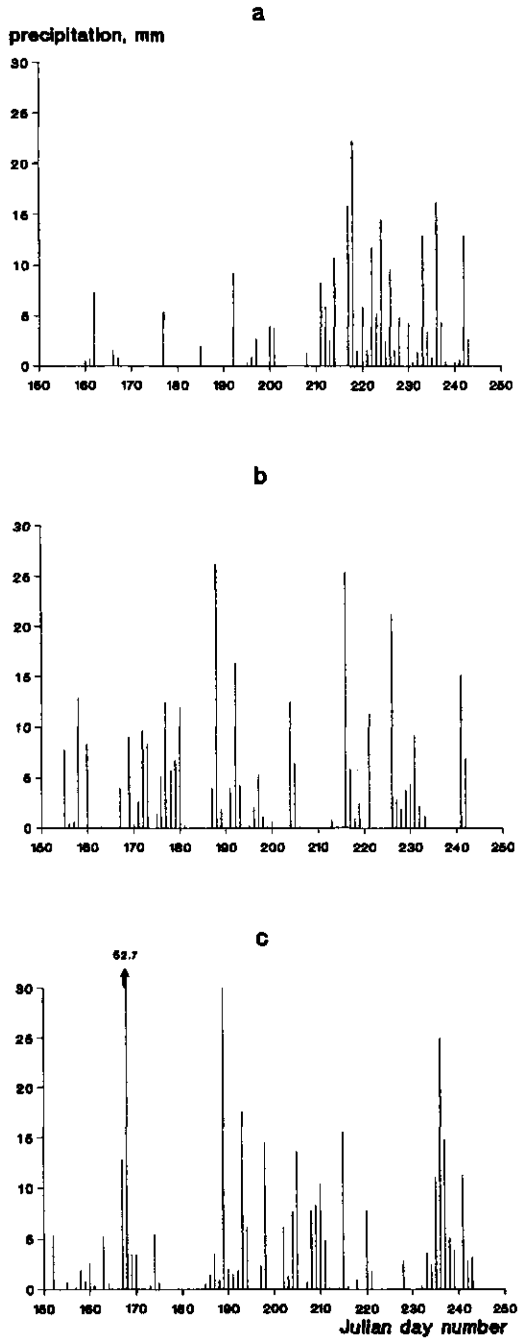

Fig. 3. Daily values of precipitation in summer (June-August = Julian day 152-Julian Day 243) at the central meteorological station in 1972 (normal, a), 1968 (wet, b), and 1965 (extremely wet, c). Data derived from Anon. (1906-1988).

Table 2. Precipitation treatments. N = normal, W = wet.

Symbol	Precipitation (mm)	
	March-May	June-August
NN	188	227
NW	188	308
WN	241	227
WW	241	308
1965	272	353

Table 3. Standard inputs in the model.

Parameter	Date or value
Measurement of soil mineral nitrogen in early spring	1 March
Fertilizer nitrogen application	15 March
Planting of tubers	1 April
End of crop growth	1 September
Soil mineral nitrogen in the 0-30 cm layer on 1 March	25 kg N per ha
Soil mineral nitrogen in the 30-60 cm layer on 1 March	25 kg N per ha
Dry weight of tubers planted	0.5 t ha^{-1}
Recovery of soil mineral N at low N nutrition	80 %
Maximum rooting depth	60 cm
Maximum total dry weight of the crop	17.5 t ha^{-1}

Results

Yield and nitrogen uptake

With the exception of the treatment involving the average rate of mineralization in 1965 on the loamy sand, the model calculations which included the various amounts of precipitation in spring showed that the maximum yield of foliage plus tubers was always obtained with the highest fertilizer nitrogen level (Fig. 4). Fig. 4 also shows that the mineralization rate had a considerable effect on the response to fertilizer nitrogen. The treatments with various amounts of precipitation in summer are not shown in Fig. 4, because precipitation in summer did not affect yield.

Like yield, maximum uptake of nitrogen by the foliage plus tubers, i.e. 300 kg N per ha, was also nearly always obtained with the highest level of fertilizer nitrogen (Fig. 5). On the sandy loam in 1965 nitrogen uptake did not exceed 200 kg N per ha at the average mineralization rate, even when 400 kg fertilizer nitrogen was applied. In this situation a serious shortage of available soil mineral nitrogen occurred. Results with various amounts of precipitation in summer are not shown here, because precipitation in summer did not affect uptake of nitrogen.

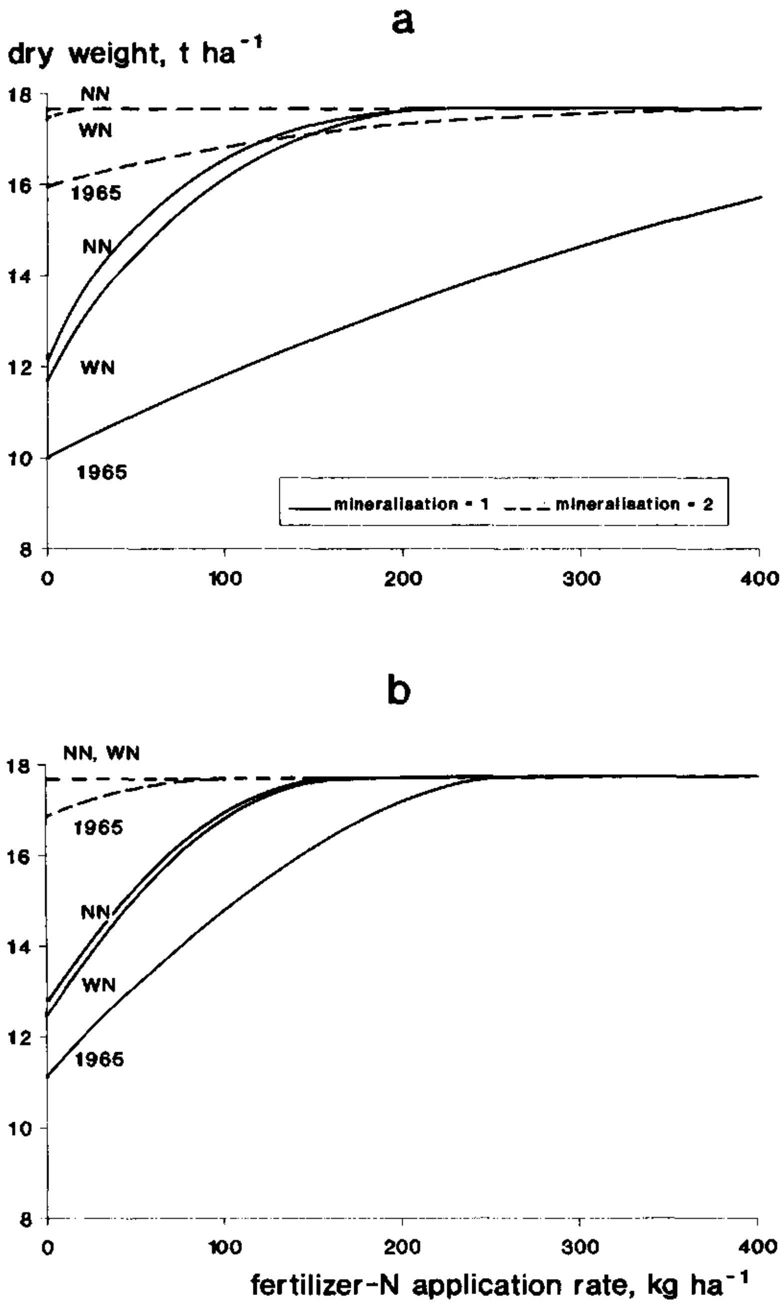

Fig. 4. Effect of fertilizer nitrogen application rate on dry weight of foliage plus tubers on the loamy sand (a) and the clay loam (b). The values 1 and 2 are the mineralization rates in kg N per ha per day. See Table 2 for meaning of symbols.

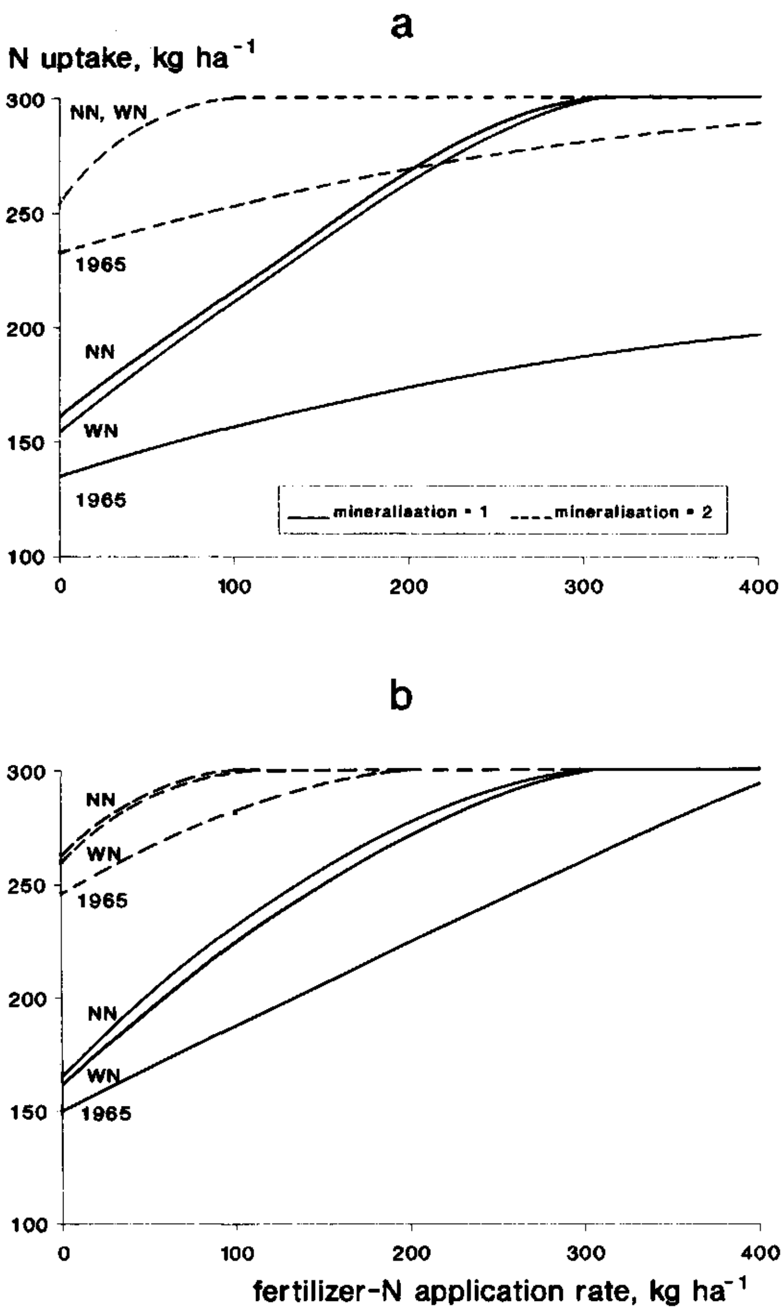

Fig. 5. Effect of fertilizer nitrogen application rate on nitrogen uptake by the foliage plus the tubers on the loamy sand (a) and the clay loam (b). The values 1 and 2 are the mineralization rates in kg N per ha per day. See Table 2 for meaning of symbols.

Nitrate leached during the growth period

Nitrate is assumed to be lost due to leaching when it moves below the root zone, i.e. the 0-60 cm layer of the soil.

Calculations with the model showed that during a spring with normal precipitation 27 kg N per ha was lost from the loamy sand and 16 kg N per ha from the clay loam when no fertilizer nitrogen was applied (Table 4). This was the result of a combination of factors: the soil was at field capacity on 1 March, rain fell in early March (day 60-69: Fig. 2a), and evaporation was low in this period. In normal and wet springs only a small percentage of fertilizer nitrogen (2-6 %) was lost from the loamy sand, whereas loss of fertilizer nitrogen from the clay loam was negligible. However, in the extremely wet spring of 1965 about 75 % of the 400 kg fertilizer nitrogen applied was lost from the loamy sand and about 35 % from the clay loam (Table 4). The same percentages were lost in 1965 at the other fertilizer levels (Fig. 6). With the exception of the very wet summer of 1965, when less than 10 kg N per ha was lost, no leaching occurred in summer (Table 4).

During normal and wet springs the rate of nitrogen mineralization hardly affected the amounts of nitrate lost from the two soils (Fig. 7). An exception was the extremely wet spring of 1965, when more nitrate was lost at the high rate than at the average rate of mineralization; the difference amounted to about 25 kg N per ha for the loamy sand and about 10 kg per ha for the clay loam.

Since fertilizer nitrogen application and rate of nitrogen mineralization appeared to have little effect on the magnitude of the losses of nitrate in normal and wet springs, the nitrate lost thus originated from nitrate already present in the deeper soil layers in early spring. Additional calculations with various amounts of soil mineral nitrogen in the 30-60 cm layer in early spring showed that the amount of nitrate

Table 4. Nitrate lost due to leaching in spring (March-May) and summer (June-August). Mineralization rate is 1 kg N per ha per day at 12 °C. 0N = no fertilizer nitrogen application; 400N = a fertilizer nitrogen application rate of 400 kg ha^{-1}. See Table 2 for meaning of symbols.

Soil type	Treatment	Nitrate leached (kg N per ha)			
		spring		summer	
		0N	400N	0N	400N
Loamy sand	NN	27	36	0	0
	NW	27	36	0	0
	WN	35	60	0	0
	WW	35	60	0	0
	1965	58	355	5	1
Clay loam	NN	16	17	0	0
	NW	16	17	0	0
	WN	23	25	0	0
	WW	23	25	0	0
	1965	44	180	3	9

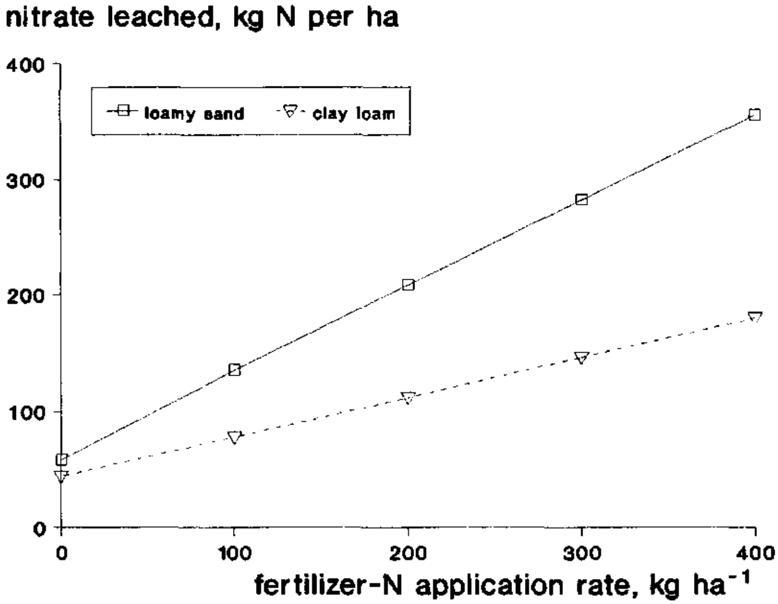

Fig. 6. Effect of fertilizer nitrogen application rate on amount of nitrate lost due to leaching from the loamy sand and the clay loam in the extremely wet spring of 1965. Mineralization rate is 1 kg N per ha per day.

lost in a normal spring heavily depended on the amount of mineral nitrogen present in this soil layer (Fig. 8). About 75 % of the mineral nitrogen present in this layer was lost from the loamy sand, and about 60 % from the clay loam.

Residual soil mineral nitrogen

The amounts of soil mineral nitrogen in the 0-60 cm layer when potato growth had ceased (1 September), i.e. residual soil mineral nitrogen, without fertilizer nitrogen and with the highest fertilizer nitrogen application rate are shown in Table 5. Without application of fertilizer, the amount of residual soil mineral nitrogen was always the smallest possible: 28 kg N per ha, i.e. 0.46 kg N per ha per cm of soil (see Section 'Materials and methods'). When 400 kg fertilizer nitrogen was applied per ha, substantially larger amounts of residual soil mineral nitrogen were found than without fertilizer nitrogen application, especially at the higher mineralization rate (Table 5). The difference tended to decrease with increasing wetness of the spring. Precipitation in summer did not affect residual soil mineral nitrogen. With the exception of 1965, the amount of residual soil mineral nitrogen was always larger in the clay loam than in the loamy sand (Table 5). With the exception of the clay loam at the higher mineralization rate, in 1965 residual soil mineral nitrogen was at the minimum level, irrespective of the rate of fertilizer nitrogen applied.

The effect of fertilizer nitrogen level on the amount of residual soil mineral nitro-

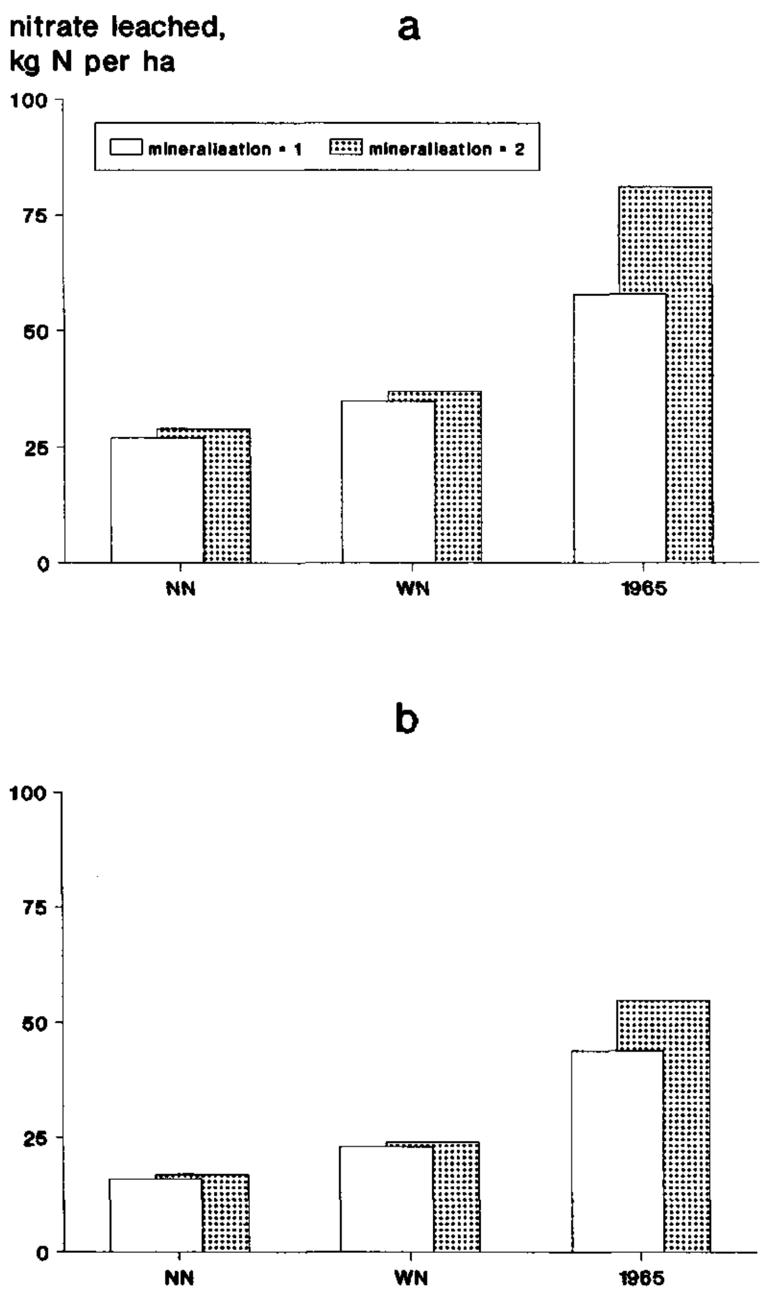

Fig. 7. Nitrate lost due to leaching from the loamy sand (a) and the clay loam (b) in a normal, a wet, and an extremely wet spring with various nitrogen mineralization rates when no fertilizer nitrogen is applied. The values 1 and 2 are the mineralization rates in kg N per ha per day. See Table 2 for meaning of symbols.

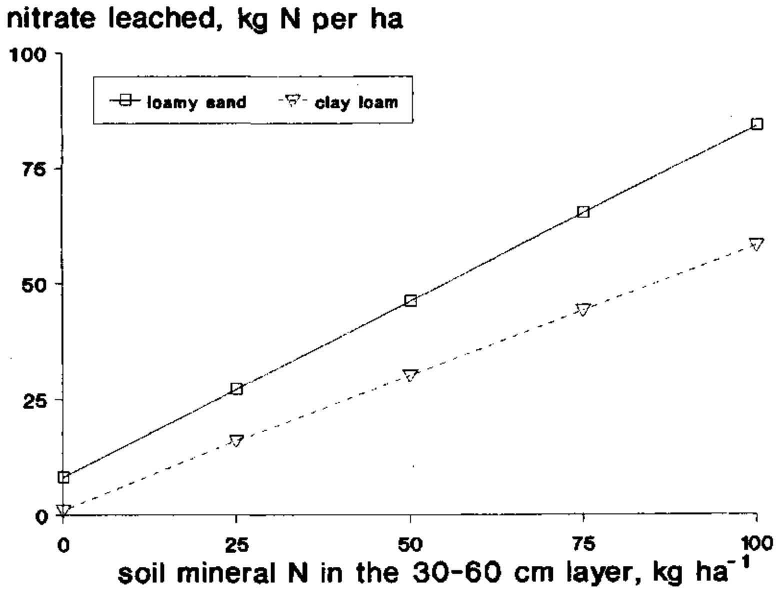

Fig. 8. Effect of soil mineral nitrogen in the 30-60 cm layer in early spring on the amount of nitrate lost due to leaching from the loamy sand and the clay loam in a spring with normal precipitation. Mineralization rate is 1 kg N per ha per day.

gen in the two soil types is shown in Fig. 9. The results presented in this figure refer to a spring and a summer with normal precipitation. At the average rate of mineralization, soil mineral nitrogen accumulated when fertilizer nitrogen levels exceeded 200 kg N per ha (Fig. 9a), but at the high mineralization rate accumulation occurred when only 100 kg N per ha was applied (Fig. 9b).

Table 5. Residual soil mineral nitrogen in the 0-60 cm layer. 0N = no fertilizer nitrogen application; 400N = a fertilizer nitrogen application rate of 400 kg ha^{-1}. See Table 2 for meaning of symbols.

Mineralization rate (kg N per ha per day)	Treatment	Residual soil mineral nitrogen (kg N per ha)			
		loamy sand		clay loam	
		0N	400N	0N	400N
1	NN	28	181	28	201
	NW	28	181	28	201
	WN	28	155	28	194
	WW	28	155	28	194
	1965	28	28	28	28
2	NN	28	376	28	397
	NW	28	376	28	397
	WN	28	349	28	389
	WW	28	349	28	389
	1965	28	28	28	138

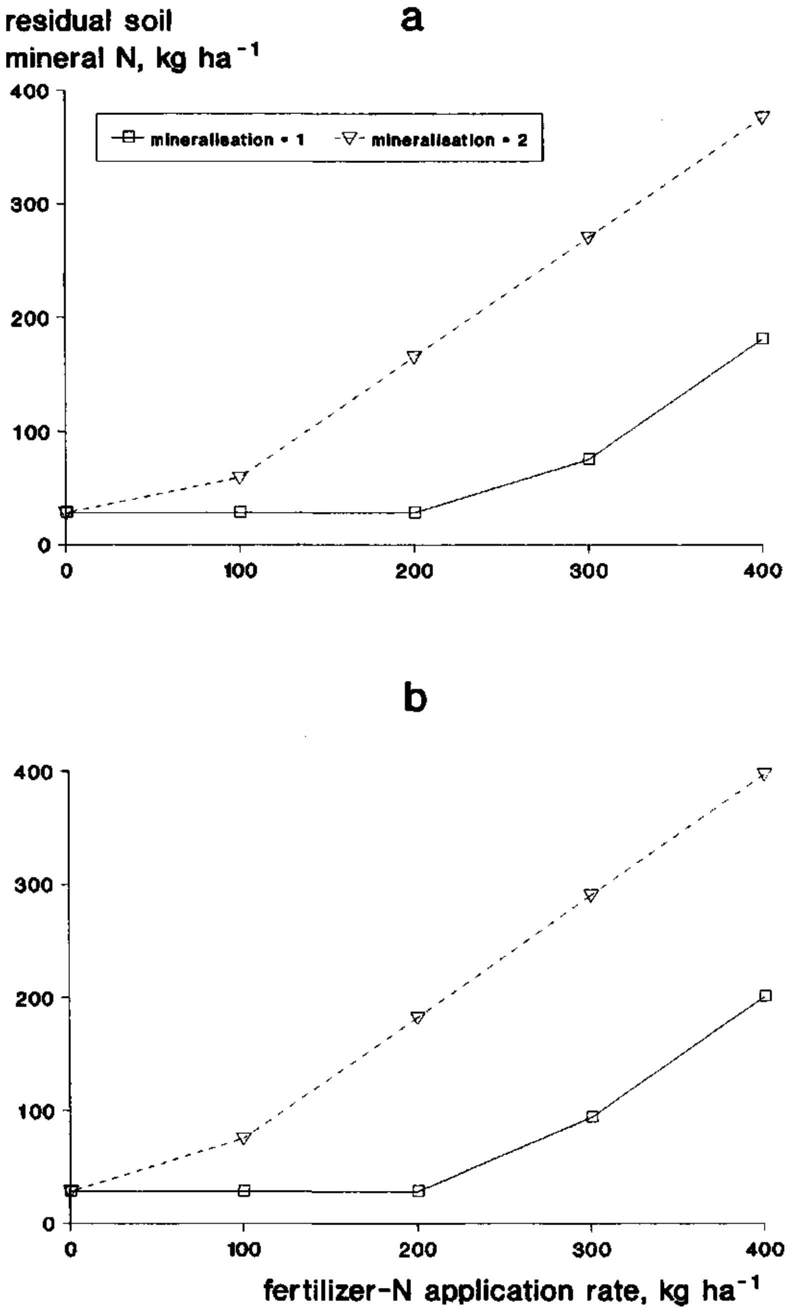

Fig. 9. Effect of fertilizer nitrogen application rate on amount of residual soil mineral nitrogen in the 0-60 cm layers of the loamy sand (a) and the clay loam (b) after a spring and summer with normal precipitation. The values 1 and 2 are the mineralization rates in kg N per ha per day.

Nitrate leaching plus accumulation of residual soil mineral nitrogen

The total loss of nitrogen due to leaching is considered to be the sum of the calculated loss during spring and summer plus the amount of soil mineral nitrogen accumulated at harvest because this nitrate will generally be leached in the following autumn and winter. In normal and wet springs the total losses of N from the loamy sand and the clay loam were similar (Figs 10 and 11). The greater loss by leaching in spring from the loamy sand was offset by the greater accumulation of residual soil mineral nitrogen in the clay loam. At the average rate of mineralization the total loss of nitrogen after normal and wet springs increased from about 20 kg N per ha at a fertilizer nitrogen application rate of 200 kg N per ha to about 190 kg N per ha at a rate of 400 kg N per ha (Fig. 10). After normal and wet springs, an application as low as 100 kg fertilizer N per ha resulted in a total loss of about 60 kg N per ha at the high rate of mineralization. At an application rate of 400 kg N per ha the total loss amounted to almost 400 kg N per ha (Fig. 11). This loss was mainly due to accumulation of residual soil mineral nitrogen.

Discussion

Nitrate leaching

The calculations showed that in normal and wet springs, nitrate present in the upper layers of soil in early spring, viz. fertilizer nitrogen, or nitrate produced in the upper layers of soil during spring, viz. mineralized soil nitrogen which is nitrified, does not move below the root zone. Duynisveld et al. (1988) also showed that there is little danger that nitrate present close to the soil surface in early March leaves the root zone of the crop. The nitrate lost during normal and wet springs thus originates from nitrate already present in the deeper soil layers. The calculations showed that a large part of the mineral nitrogen present in the 30-60 cm layer at the end of the winter was lost due to leaching in spring. This implies that the presence during winter of a cover crop that absorbs nitrogen from the 30-60 cm layer will help to minimize leaching not only during the winter period, but also during spring.

The calculations also showed that substantial leaching of fertilizer nitrogen (up to 75 % of the amount applied) or of nitrogen mineralized in spring occurred during the extremely wet spring of 1965. Under such conditions, nitrate originally present in the upper layers of soil then moves below the root zone. The chance of such wet springs occurring is, however, small: only about 5 % (Fig. 1).

It was shown that leaching of nitrate did not occur at all during dry to wet summers, and was negligible during extremely wet summers. Leaching did not occur because the soils hardly reached field capacity in summer due to high evapotranspiration (de Willigen, 1986).

Residual soil mineral nitrogen

The amount of residual soil mineral nitrogen as calculated by the model is the dif-

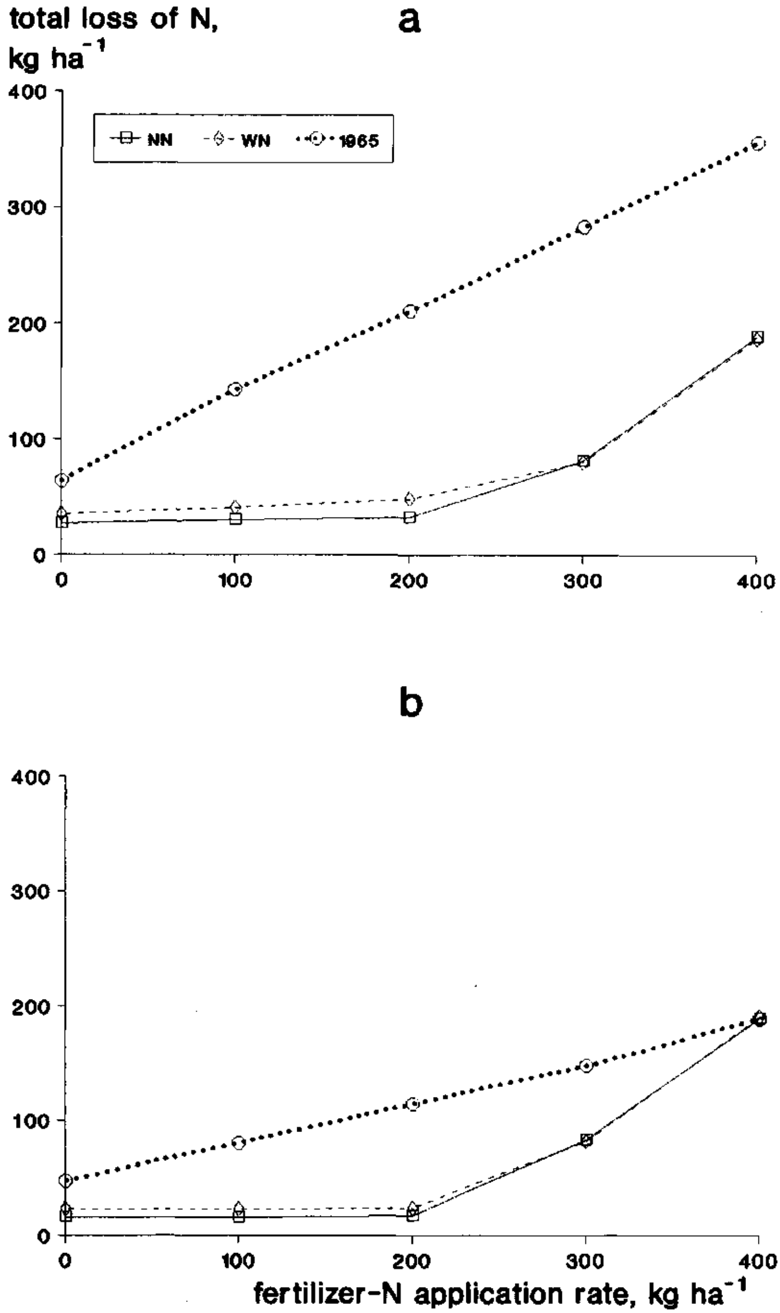

Fig. 10. Total loss of nitrogen due to leaching in spring and accumulation of residual soil mineral nitrogen in the loamy sand (a) and the clay loam (b) after a normal, a wet, and an extremely wet spring. Mineralization rate is 1 kg N per ha per day.

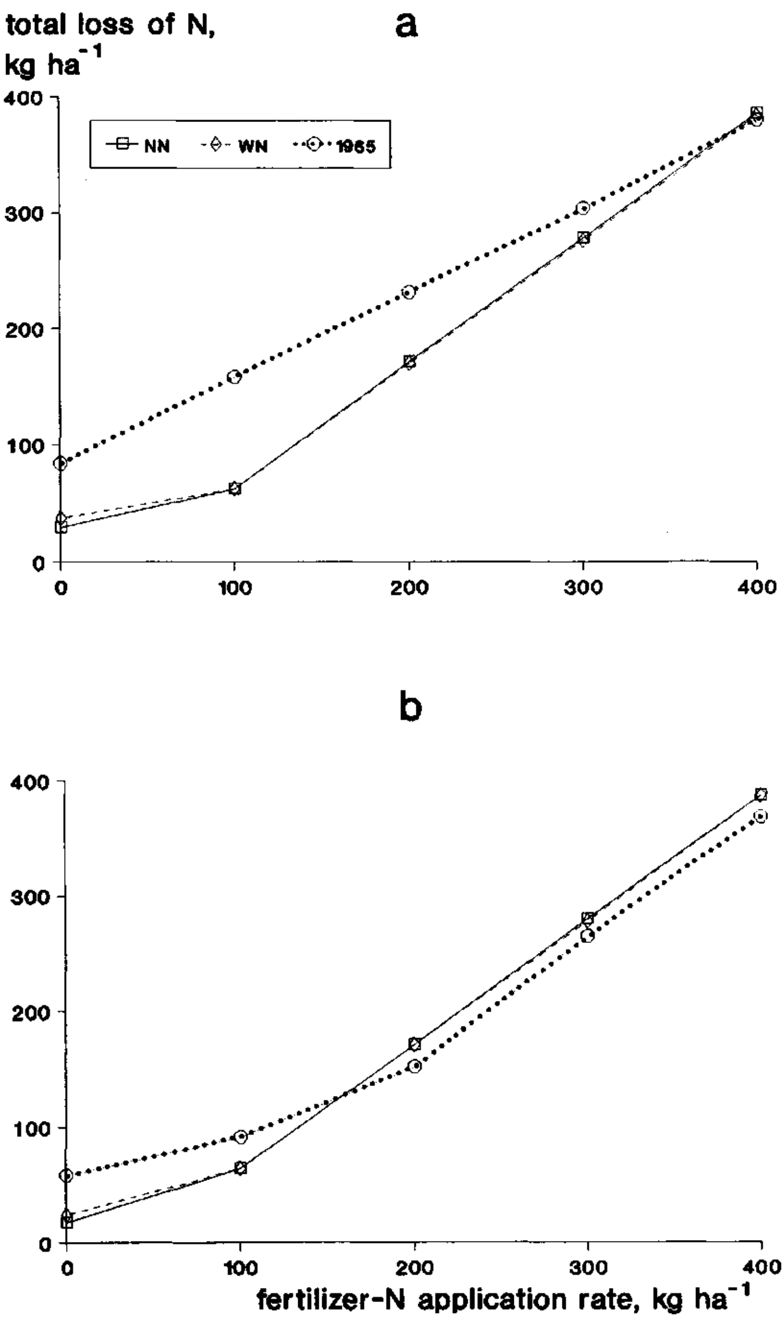

Fig. 11. Total loss of nitrogen due to leaching in spring and accumulation of residual soil mineral nitrogen in the loamy sand (a) and the clay loam (b) after a normal, a wet, and an extremely wet spring. Mineralization rate is 2 kg N per ha per day.

ference between, on the one hand, the sum of the initial amount of soil mineral nitrogen (1 March), the amount of fertilizer nitrogen applied, and the amount of nitrogen mineralized from 1 March onwards, and on the other hand, the sum of the amount of nitrogen recovered by the tops and tubers of the potato crop, the amount of nitrogen leached from 1 March onwards, and the amount of nitrogen not recovered by the tops and tubers. When the crop absorbs nitrate from soil, less nitrogen appears in the foliage and tubers than 'disappears' from soil, even when there is no leaching. This 'disappearance' is set in the model to vary between 20 and 35 % as described earlier (Section 'Materials and methods'). It covers immobilization of nitrogen by the microbial biomass, denitrification, ammonia volatilization, and incorporation of nitrogen into fibrous roots, processes which are not explicitly described in the model. Nitrogen which is present in leaves shed during senescence is also assumed to be included in the fraction of nitrogen that disappears. The contribution of the other processes which are not explicitly described by the model may vary depending on site and weather conditions, thus making the value of the amount of the nitrogen not recovered by the tops and tubers in the balance sheet rather uncertain. However, attempts to describe processes in more detail have as yet not seemed to improve the validity of models used for practical purposes (de Willigen & Neeteson, 1985; Neeteson & van Veen, 1988).

After normal and wet springs the mineralization rate in the soil and the soil type did not affect the amount of residual soil mineral nitrogen. However, after the extremely wet spring of 1965, at the high mineralization rate, and at the higher levels of fertilizer nitrogen application, more residual soil mineral nitrogen was calculated to be present in the clay loam than in the loamy sand due to the fact that the nitrate supply by the soil exceeded crop demand. In the loamy sand more of this surplus was lost due to leaching, so that less was left unused by the crop and could thus be found as residual soil mineral nitrogen.

Under average conditions of precipitation and mineralization, residual soil mineral nitrogen started to accumulate at fertilizer nitrogen application rates exceeding 200 kg N per ha. At the high level of nitrogen mineralization, however, accumulation began when the application rate was only 100 kg N per ha. If the optimum application rates of fertilizer nitrogen had been applied, i.e. at the average rate of mineralization about 200 kg N per ha on the loamy sand and about 150 kg N per ha on the clay loam and at the high rate of mineralization 0-20 kg N per ha (Fig. 4), no accumulation of residual soil mineral would have occurred (Fig. 9). In a series of nitrogen-fertilizer trials with starch potatoes on sandy soils and cut-over peat soils, Wadman et al. (1990) found that residual soil mineral nitrogen in the 0-60 cm layer averaged 27 kg N per ha without application of fertilizer nitrogen and 84 kg N per ha with the optimum application rate of fertilizer nitrogen. Thus they found an accumulation of 57 kg residual soil mineral N per ha. The difference between the amount accumulated according to calculations in the model and the findings of Wadman et al. is probably due to the assumption in the model that 20 to 30 % of soil mineral nitrogen 'disappears'. Since residual soil mineral nitrogen in the trials of Wadman et al. was determined about 45 days later than was assumed in the model, it is quite possible that a large part of the nitrogen present in the leaves shed during senescence of the starch potatoes had already mineralized at that time. Another explanation for the larger amount of residual nitrogen accumulated could be that nitrogen uptake by, and growth of, the starch potatoes were impeded by drought, because the growing seasons of 1983-1985, the period in which the trials were performed (Wadman et al., 1990), were rather dry.

Total amount of nitrogen lost

If the currently recommended amounts of fertilizer nitrogen (Neeteson, 1989a) of 305 kg N per ha for the loamy sand and 265 kg N per ha for the clay loam had been applied and the mineralization rate was average, the total loss due to leaching in a normal spring and due to accumulation of residual soil mineral nitrogen would have been 88 kg N per ha for loamy sand and 45 kg N per ha for clay loam. At the high mineralization rate, the total loss from the loamy sand would have been 288 kg N per ha and that from the clay loam 239 kg N per ha. Assuming that the precipitation surplus is 300 mm water – the usual amount in the Netherlands – the EEC maximum permissible concentration for drinking water of 11.3 mg nitrate-N per litre (Anon., 1980) is reached when 34 kg N per ha is leached out. This means that the EEC standard is exceeded when potatoes are given the currently recommended amounts of nitrogen, especially so when mineralization rates are high. In a previous paper (Neeteson, 1989b) it was shown that a 25 % reduction in the recommended amounts of fertilizer nitrogen for potatoes did not affect yield. If the above-mentioned recommended amounts of nitrogen are reduced by 25 %, the total loss of nitrogen would be 33 kg N per ha in the case of the loamy sand and 22 kg N per ha in the case of the clay loam at the average rate of mineralization. Thus, when the currently recommended amounts of fertilizer nitrogen for potatoes are reduced by 25 %, it appears that under normal conditions a high yield will be obtained without exceeding the maximum permissible nitrate concentration in water to be used for human consumption. However, at the high rate of mineralization, a reduction of the recommended amounts of nitrogen by 25 % would still result in excessive losses: 205 and 167 kg N per ha for the loamy sand and the clay loam, respectively. Since it is difficult to predict mineralization rates for individual fields, research aimed at finding simple ways to determine mineralization levels by means of incubation or chemical extraction (Stanford, 1981) should be continued. When the mineralization rate of a specific field can be predicted, the recommended amount of fertilizer nitrogen can be lowered considerably when mineralization rates are high; severe losses of nitrogen can thus be avoided.

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Summary

Plants take up nitrogen (N) from the soil in an inorganic form as ammonium and/or nitrate ions. This nitrogen, also referred to as mineral nitrogen, originates from fertilizers, mineralization of soil organic matter, and atmospheric deposition. For high yields, crops take up 200-400 kg N per ha. An example of a crop having a relatively low nitrogen requirement is oats; in the case of intensively used grassland the requirement is high (400 kg N per ha). Fertilization is necessary to meet the nitrogen requirement of crops because (1) nitrogen mineralization and atmospheric deposition during the growing season can vary considerably, but usually do not contribute more than 100 and 25 kg N per ha, respectively, (2) losses due to denitrification, leaching of nitrate, and volatilization of ammonia occur, and (3) mineral nitrogen can be immobilized in organic matter. Fertilizer materials may be inorganic or organic. This thesis deals with application of inorganic nitrogen fertilizers to potatoes and sugar beet for the purpose of developing nitrogen fertilizer recommendations for farmers that will not only result in high yields of good quality, but will also limit nitrogen losses to the environment.

The current nitrogen fertilizer recommendations are based on results obtained from a very large number of field experiments with potatoes and sugar beet. These experiments were conducted in the period 1973-1982 for the purpose of establishing recommendations on the basis of soil test results. In every trial the amount of soil mineral nitrogen present at the end of winter was determined. Six or seven rates of fertilizer nitrogen were applied in spring, from 0 to 400 kg N per ha to potatoes and from 0 to 250 kg N per ha to sugar beet. At the end of the growing season the yields obtained at the different nitrogen application levels and, for sugar beet, also the sugar contents were determined. The optimum rate of nitrogen application was then assessed for each experimental field from the relation between fertilizer nitrogen application rate and crop yield. For each experimental field the amount of soil mineral nitrogen present at the end of winter and the optimum nitrogen application rate were known. When for all experiments the amount of soil mineral nitrogen was plotted against the optimum rate of fertilizer nitrogen, this rate was found to decrease with increasing amounts of mineral nitrogen in the soil. The current recommendations for potatoes and sugar beet were derived from the linear relation between the amount of soil mineral nitrogen and the optimum fertilizer nitrogen application rate as found in these experiments.

Because in the current recommendations little or no account is taken of the effects of soil type and recently applied organic manures on the fertilizer nitrogen requirement of crops, attempts were made to refine these recommendations for potatoes and sugar beet, as described in Chapters 2-5. In this investigation use was made of the same experimental fields as used for establishing the current recommendations.

In Chapter 2, the response of the crop to fertilizer nitrogen, the so-called nitrogen response curve, is described by means of mathematical equations enabling an

exact calculation to be made of the optimum fertilizer nitrogen application rate and to estimate the error associated with the calculated optimum. It should be noted that the current recommendations are based on optima whose precision is not known, as they were derived from hand-drawn curves. For potatoes as well as for sugar beet the nitrogen response curves could be described adequately by means of an exponential equation. This equation included a linear segment so that the curve could decline at nitrogen rates exceeding the amount at which maximum yield was obtained. The 95 % confidence interval for the economically optimum nitrogen rate, calculated for each experiment, was often very wide. It exceeded 300 kg N per ha in 60 % of the potato experiments and in 46 % of the sugar beet trials. The large confidence intervals were to be attributed to the large variability among replicate yields obtained with a certain nitrogen fertilizer application rate and to the fact that the curves generally ran a level course near the optimum.

In Chapter 3, an analysis of variance of the results of potato and sugar-beet experiments is presented, for the purpose of establishing the effect of amount of soil mineral nitrogen at the end of winter, soil type, and recently applied organic manures on crop response to fertilizer nitrogen. It was found that all these factors significantly affected the response of potatoes and sugar beet to nitrogen. The response decreased with increasing amounts of soil mineral nitrogen. On sandy soils the nitrogen fertilizer requirement of potatoes was about 100 kg N per ha higher, and that of sugar beet about 20 kg N per ha higher, than on loam and clay soils. Where organic manure had been applied (as slurry or green-manure crop) prior to fertilizer nitrogen application, the fertilizer nitrogen requirement of both crops was 15-50 kg N per ha lower. On the basis of these results it may be concluded that for making nitrogen fertilizer recommendations for potatoes and sugar beet not only the amount of soil mineral nitrogen, but also the soil type and recently applied organic manure should be taken into account.

In Chapter 4, fertilizer recommendations were presented for potatoes and sugar beet as calculated on the basis of results described in Chapter 3. However, the average fertilizer nitrogen rates to be applied according to these recommendations were higher than those to be applied according to the current recommendations: the difference was 30 kg N per ha for potatoes and 25 kg N per ha for sugar beet. The more refined recommendations gave, on average, slightly higher yields, but the differences were not significant. Since a large segment of the nitrogen response curve of especially potatoes, but also of sugar beet, runs a level course, thus obviating a reliable determination of the optimum (Chapter 2), there was little difference between the yields obtained according to the two advisory methods, in spite of a difference in recommended rates of fertilizer nitrogen. Correct nitrogen fertilizer recommendations should recommend amounts large enough to bring about high crop yields, but low enough to prevent waste of fertilizer.

Because the two methods resulted in equally high yields, but with less fertilizer nitrogen to be applied according to the current method, it may be concluded that there is no reason to replace the current recommendations. However, the question may be raised to what extent the current recommendations can be lowered without seriously affecting yields. This was investigated for potatoes and sugar beet (Chapter 5). When it is assumed that the yield deficits, i.e. the deviations of the yields from those obtained with the measured optimum application rates of fertilizer nitrogen, on average are not allowed to exceed 2 %, the currently recommended application rate of fertilizer nitrogen for potatoes can be reduced by about 30 %. When it is assumed that the probability of yield deficits larger than 5 % is not allowed to exceed 5 %, the currently recommended fertilizer rate can be reduced by 25 %. The current recommendation for sugar beet cannot be lowered, because the average yield deficit with the recommended application rates is already 2 %. It is concluded that the current recommendation for potatoes can be lowered by 25 % without seriously affecting yield and that the current recommendation for sugar beet should be maintained.

In Chapter 5, attention is also paid to the effect of a change in the ratio of cost of fertilizer nitrogen to price of crop produce on the optimum application rate of fertilizer nitrogen. It is quite well possible that the numerical value of this ratio will increase in the future when the current low cost of fertilizer nitrogen will rise, not only due to higher energy costs, but also due to a levy imposed on fertilizers. A change in the ratio proved to have a much larger effect on potatoes than on sugar beet. A fivefold increase in the ratio decreased the optimum for potatoes by 50 % and for sugar beet by only 20 %. However, it also considerably decreased farm income due to lower yields. The decrease was more than Dfl. 800 per ha for potatoes and more than Dfl. 400 for sugar beet.

In Chapters 2-5, nitrogen fertilizer recommendations were discussed in which the many simultaneously occurring processes of the nitrogen cycle are not explicitly taken into account, e.g. mineralization, nitrate leaching and nitrogen uptake by the crop as affected by growth stage and availability of nitrogen. The recommendations discussed are therefore only valid for average conditions. For more site-specific nitrogen fertilizer recommendations a dynamic simulation model for the nitrogen response of potatoes was developed.

In Chapter 6, characteristics of the model are presented. The model calculates on a daily basis dry-matter production of, and nitrogen uptake by, potatoes. Mineralization of soil nitrogen and vertical redistribution of nitrate in the soil on a daily basis are calculated as well. The model inputs required are the amount of soil mineral nitrogen at the end of winter, amount and time of fertilizer nitrogen application, planting date, expected maximum yield and maximum rooting depth, soil type, daily values of precipitation surplus, and daily values of soil temperature. These inputs are readily available to the farmer at the time advice is required. The model was used to predict yields at seven levels of fertilizer nitrogen in each of 61 trials. To investigate whether the model could give a proper description of the response of potatoes to nitrogen, calculations were performed with actually observed or measured input data. The model gave a reasonably good description of the yields obtained: the calculated yield differed significantly from the measured yield in only 20 of the 427 calculations performed. Next, the calculations were performed with the input data available to the farmer at the time advice is required. Average values were used for weather data and expected maximum yield. As could be expected in such situations, the model gave less accurate yield predictions of the yields than when actual input data were used. However, the optimum application rates of fertilizer nitrogen, which were derived from yields predicted at the various fertilizer nitrogen levels, were predicted accurately in 84 % of the trials, which is about as good a result as that obtained with the currently used nitrogen fertilizer recommendations (Chapter 4). It is to be expected that the performance of the model can be improved, particularly when reliable predictions of the mineralization rate at a specific site can be obtained.

A simulation model can also be used to demonstrate the effect of fertilizer nitrogen application on the environment. In Chapter 7 the amount of nitrate lost due to leaching during the growth of potatoes and the accumulation of mineral nitrogen in the soil at harvest time was estimated with the model presented in the previous chapter. It was calculated that nitrate was always lost in a normal or a wet spring due to leaching, especially from light soils. The nitrate lost originated from mineral nitrogen present at the end of winter in the 30-60 cm layer of soil. Soil nitrogen mineralized during spring and fertilizer nitrogen were calculated to be lost only in extremely wet springs. Under normal conditions, accumulation of nitrogen in the soil at harvest time occurred at applications of fertilizer nitrogen exceeding 200 kg N per ha; at high rates of mineralization it already occurred at applications exceeding 100 kg N per ha. The accumulation was somewhat larger in heavy soils than in light soils. The accumulated soil mineral nitrogen can be regarded as a nitrogen loss, because this nitrogen is potentially subject to being lost due to leaching in autumn and winter. When the current nitrogen fertilizer recommendations for potatoes are reduced by 25 % (Chapter 4), the total losses due to leaching in spring and accumulation at harvest would not result in nitrate concentrations in the groundwater exceeding the EEC standard for maximally permissible nitrate concentration in water used for human consumption. Measures intended to further reduce fertilizer nitrogen application rates are thus not likely to contribute to environmental protection, but will certainly lead to a considerable decrease in farm income (Chapter 5). When high mineralization rates are likely to occur, however, the total losses would exceed 150 kg N per ha resulting in nitrate concentrations in the groundwater substantially exceeding the maximally permissible concentration.

Samenvatting

Bepaling van de behoefte aan kunstmeststikstof van aardappelen en suikerbieten

Planten nemen stikstof (N) uit de bodem op in anorganische vorm als ammonium- en/of nitraationen. Deze stikstof, die ook wel minerale stikstof wordt genoemd, is afkomstig van bemesting, mineralisatie van organische stof en atmosferische depositie. Voor een goede opbrengst nemen gewassen 200-400 kg N per ha op. Een voorbeeld van een gewas met een betrekkelijk lage stikstofbehoefte (200 kg N per ha) is haver; in het geval van intensief gebruikt grasland is de stikstofbehoefte hoog (400 kg N per ha). De bijdrage van de mineralisatie bedraagt in het groeiseizoen doorgaans ongeveer 100 kg N per ha, maar kan zeer sterk variëren; de atmosferische depositie bedraagt ongeveer 25 kg N per ha. Het is echter onvermijdelijk dat er verliezen aan minerale stikstof optreden (denitrificatie, nitraatuitspoeling, ammoniakvervluchtiging) en dat er minerale stikstof wordt vastgelegd in de organische stof (immobilisatie). Daarom is bemesting nodig om in de stikstofbehoefte van gewassen te voorzien. Bemesting kan plaatsvinden met organische meststoffen en/of anorganische (kunst)meststoffen. Dit proefschrift behandelt bemesting van aardappelen en suikerbieten met kunstmest. Het doel is tot zodanige bemestingsadviezen voor de boeren te komen dat een hoge gewasopbrengst van goede kwaliteit behaald wordt terwijl de stikstofverliezen naar het milieu beperkt blijven.

De huidige bemestingsadviezen zijn gebaseerd op resultaten die afkomstig zijn van een zeer groot aantal veldproeven met aardappelen en suikerbieten. Deze proeven zijn in de periode 1973-1982 aangelegd met als doel adviezen te baseren op grondonderzoek. In elke proef werd de hoeveelheid minerale bodemstikstof aan het eind van de winter gemeten. Vervolgens werden in het voorjaar zes of zeven kunstmeststikstofhoeveelheden toegediend, bij aardappelen variërend van 0 tot 400 en bij suikerbieten van 0 tot 250 kg N per ha. Ten slotte werden aan het eind van het groeiseizoen de gewasopbrengsten, en bij de suikerbieten tevens de kwaliteit (suikergehalte), bepaald bij de verschillende stikstofhoeveelheden. Uit het verband tussen de stikstofgift en de gewasopbrengsten werd vervolgens per proefveld de optimale stikstofgift bepaald. Per proefveld was dus de hoeveelheid minerale bodemstikstof aan het eind van de winter en de optimale kunstmeststikstofgift bekend. Werd nu voor alle proefvelden de hoeveelheid minerale bodemstikstof uitgezet tegen de optimale stikstofgift, dan bleek dat de optimale stikstofgift afnam met toenemende hoeveelheid minerale bodemstikstof. De huidige adviezen voor aardappelen en suikerbieten zijn dan ook afgeleid van het rechtlijnige verband tussen de hoeveelheid minerale bodemstikstof en de optimale stikstofgift zoals dat in deze proeven gevonden was.

In de hoofdstukken 2-5 van dit proefschrift is getracht de huidige adviezen voor aardappelen en suikerbieten te verfijnen. In de huidige adviezen wordt namelijk niet of nauwelijks rekening gehouden met de invloed van de grondsoort en recent toegediende organische meststoffen op de behoefte van de gewassen aan kunstmeststikstof. Het onderzoek is verricht met behulp van dezelfde proefvelden die gebruikt zijn voor het opstellen van de huidige bemestingsadviezen.

In hoofdstuk 2 is de reactie van het gewas op toegediende stikstof, de zogenaamde stikstofreactiekromme, beschreven met wiskundige vergelijkingen teneinde de optimale stikstofgift exact te kunnen berekenen en aan te kunnen geven met welke fout het berekende optimum behept is. Opgemerkt dient te worden dat de huidige adviezen zijn gebaseerd op optima waarvan de nauwkeurigheid niet bekend is, omdat de optima zijn afgeleid van met de hand getrokken stikstofreactiekrommen. Zowel bij aardappelen als bij suikerbieten bleken de stikstofreactiekrommen goed beschreven te kunnen worden met een exponentiële vergelijking. In deze vergelijking was ook een rechtlijnig stuk opgenomen, opdat de kromme kon dalen bij stikstofgiften die groter waren dan de gift waarmee de maximale opbrengst werd bereikt. Het 95 %-betrouwbaarheidsinterval van de per proefveld berekende economisch optimale stikstofgift bleek vaak erg groot te zijn. Dit interval was groter dan 300 kg N per ha in 60 % van de aardappelproefvelden en in 46 % van de suikerbietenproefvelden. De grote betrouwbaarheidsintervallen werden toegeschreven aan de grote variatie in opbrengsten die in het algemeen werd waargenomen tussen de herhalingen van eenzelfde stikstofgift en aan het feit dat de krommen in het algemeen een vlak verloop hadden in de buurt van het optimum.

In hoofdstuk 3 zijn de resultaten beschreven van een variantie-analyse die uitgevoerd is met de gegevens van de aardappel- en suikerbietenproefvelden, teneinde vast te stellen welke invloed de hoeveelheid minerale bodemstikstof aan het eind van de winter, de grondsoort, en recent toegediende organische bemesting hebben op de reactie van het gewas op kunstmeststikstof. Deze factoren bleken alle een significant effect te hebben op de reactie van aardappelen en suikerbieten op kunstmeststikstof. De reactie nam af bij toenemende hoeveelheid minerale bodemstikstof. Op zandgronden was de behoefte aan kunstmeststikstof bij aardappelen ongeveer 100 kg N per ha en bij suikerbieten ongeveer 20 kg N per ha groter dan op zavel- en kleigronden. Als er organische mest was toegediend (dunne mest of groenbemesters) voordat de kunstmeststikstof werd gegeven, was de behoefte aan kunstmeststikstof bij beide gewassen 15-50 kg N per ha lager dan wanneer er geen organische bemesting had plaatsgevonden. Op grond van deze resultaten kan geconcludeerd worden dat in stikstofbemestingsadviezen voor aardappelen en suikerbieten niet alleen rekening gehouden dient te worden met de hoeveelheid minerale bodemstikstof, maar ook met de grondsoort en met recent toegediende organische bemesting.

In hoofdstuk 4 zijn dan ook bemestingsadviezen voor aardappelen en suikerbieten opgesteld op basis van de resultaten die beschreven zijn in hoofdstuk 3. Met deze adviezen bleek echter gemiddeld meer kunstmeststikstof nodig te zijn dan met de huidige adviezen: het verschil was 30 kg N per ha bij aardappelen en 25 kg N per ha bij suikerbieten. Er werden wel gemiddeld iets hogere opbrengsten behaald met de meer verfijnde adviezen, maar de verschillen waren niet significant. Omdat de stikstofreactiekrommen van met name aardappelen, maar ook van suikerbieten, voor een groot gedeelte vlak verlopen en daardoor het optimum niet betrouwbaar is te bepalen (hoofdstuk 2), verschilden de opbrengsten behaald met de twee adviesmethoden weinig van elkaar, ondanks een verschil in geadviseerde hoeveelheden stikstof. Een goed stikstofbemestingsadvies dient stikstofhoeveelheden te adviseren die hoog genoeg zijn om een hoge gewasopbrengst te bewerkstelligen, en die laag genoeg zijn om verspilling van stikstof te vermijden. Aangezien met beide adviesmethoden even hoge opbrengsten werden behaald, en hiervoor minder kunstmeststikstof nodig was met de huidige methode, kan geconcludeerd worden dat er geen reden is om de huidige adviezen te vervangen. De vraag kan nu echter gesteld worden in hoeverre de huidige adviezen verlaagd kunnen worden, zonder dat dit een negatief effect heeft op de gewasopbrengsten. Dit is in hoofdstuk 5 nagegaan voor aardappelen en suikerbieten. Ervan uitgaande dat een gemiddelde opbrengstderving van 2 % ten opzichte van de opbrengst verkregen met de optimale stikstofbemesting acceptabel is, bleek het huidige stikstofbemestingsadvies voor aardappelen met ongeveer 30 % verlaagd te kunnen worden. Wanneer gesteld wordt dat de kans op zeer grote opbrengstdervingen, dat wil zeggen opbrengstdervingen groter dan 5 %, niet groter mag zijn dan 5 %, dan zou het advies voor aardappelen met ongeveer 25 % verlaagd kunnen worden. Het huidige advies voor suikerbieten bleek niet verlaagd te kunnen worden, omdat met dit advies gemiddeld reeds 2 % opbrengstderving werd verkregen. Geconcludeerd werd dan ook dat het advies voor aardappelen zonder al te grote effecten op de opbrengst met 25 % verlaagd kan worden en dat het huidige advies voor suikerbieten gehandhaafd dient te blijven.

In hoofdstuk 5 is ook aandacht geschonken aan het effect op de optimale stikstofgift van een verandering in de verhouding tussen de kosten van kunstmeststikstof en de prijs die verkregen wordt voor de oogstprodukten. Het is namelijk niet onwaarschijnlijk dat deze verhouding in de toekomst zal veranderen, wanneer de kunstmest duurder wordt als gevolg van stijgende energiekosten en/of heffingen op het gebruik van kunstmest. Een verandering in de verhouding tussen de kosten van kunstmest en de prijs voor oogstprodukten bleek een veel grotere invloed te hebben op de economisch optimale stikstofgift voor aardappelen dan op die voor suikerbieten. Wanneer de kunstmest vijfmaal zo duur zou worden, bij een gelijkblijvende prijs voor de oogstprodukten, zou de optimale kunstmeststikstofgift voor aardappelen gemiddeld ongeveer 50 % lager worden en die voor suikerbieten slechts ongeveer 20 %. Door lagere gewasopbrengsten zal het inkomen van de boer hier sterk onder te lijden hebben. In het genoemde voorbeeld zal het inkomen ruim 800 gulden lager zijn per ha aardappelen en ruim 400 gulden per ha suikerbieten.

In de hoofdstukken 2-5 zijn stikstofbemestingsadviezen besproken die niet expliciet rekening houden met de vele dynamische processen waaraan stikstof in het groeiseizoen onderhevig is, zoals mineralisatie van stikstof, nitraatuitspoeling, en opname door het gewas in afhankelijkheid van groeistadium van het gewas en beschikbaarheid van stikstof. De besproken adviezen zijn dan ook alleen geldig voor gemiddelde omstandigheden. Teneinde te komen tot een meer perceelsgewijze advisering van de stikstofbehoefte van een gewas is een dynamisch simulatiemodel voor de reactie van aardappelen op stikstof ontwikkeld.

In hoofdstuk 6 worden kenmerken van het model besproken. Er kan mee worden berekend hoeveel drogestof er door de aardappelen van dag tot dag wordt geproduceerd en hoeveel stikstof van dag tot dag uit de bodem wordt opgenomen. Mineralisatie van stikstof en verticale verplaatsing van stikstof door de bodem worden eveneens op een dagelijkse basis berekend. De invoergegevens die hiervoor nodig zijn, zijn de hoeveelheid minerale bodemstikstof aan het eind van de winter, hoeveelheid en tijdstip van stikstofbemesting, pootdatum, verwachte maximale opbrengst en maximale bewortelingsdiepte, grondsoort en dagelijkse weersgegevens (neerslagoverschot, bodemtemperatuur). Op het moment dat de boer wil gaan bemesten en het model hiervoor wil raadplegen, heeft hij de gevraagde gegevens tot zijn beschikking of kan hij deze op eenvoudige wijze verkrijgen. Met het model zijn de opbrengsten bij zeven kunstmeststikstofhoeveelheden op 61 proefvelden voorspeld. Om na te gaan of het model in staat is een goede beschrijving te geven van de reactie van aardappelen op stikstof zijn eerst berekeningen uitgevoerd met de werkelijk waargenomen of gemeten invoergegevens. Met het model werden op die wijze zeer aanvaardbare resultaten behaald: in slechts 20 van de 427 uitgevoerde berekeningen bleek de voorspelde opbrengst significant af te wijken van de gemeten opbrengst. Vervolgens werden berekeningen uitgevoerd met die gegevens die de boer tot zijn beschikking heeft op het moment dat hij wil gaan bemesten. Voor de overige gegevens (weersgegevens, verwachte maximale opbrengst) werd van gemiddelde waarden uitgegaan. Zoals verwacht mocht worden, werden hiermee de opbrengsten minder goed voorspeld dan wanneer van de werkelijk gemeten gegevens werd uitgegaan. Werd vervolgens de economisch optimale stikstofgift berekend uit de aldus voorspelde opbrengsten bij de verschillende stikstofhoeveelheden, dan bleek de optimale stikstofgift in 84 % van de gevallen goed voorspeld te zijn. Deze doeltreffendheid komt ongeveer overeen met die van de huidige adviesmethode (hoofdstuk 4). Verwacht wordt dat de doeltreffendheid van het model groter zal worden wanneer het mogelijk is om vooraf perceelsgewijs betrouwbare uitspraken te doen over met name de te verwachten mineralisatiesnelheid.

Een simulatiemodel kan ook gebruikt worden om de milieu-effecten van het toedienen van stikstof aan te geven. In hoofdstuk 7 is met het in het vorige hoofdstuk gepresenteerde model nagegaan hoeveel nitraat er gedurende het groeiseizoen uitspoelt bij aardappelen en hoeveel minerale stikstof zich ophoopt in de bodem ten tijde van de oogst. Uit de berekeningen bleek dat er in een normaal of nat voorjaar altijd enige uitspoeling van nitraat plaatsvindt, met name op lichte gronden. De uitgespoelde stikstof was afkomstig van minerale stikstof die aan het eind van de winter in de bodemlaag onder de bouwvoor aanwezig was. Stikstof die in het voorjaar gemineraliseerd wordt en kunstmeststikstof bleken alleen onder zeer extreme weersomstandigheden uit te spoelen in het voorjaar. Onder normale omstandigheden bleek stikstof zich op te hopen in het bodemprofiel bij stikstofgiften die hoger waren dan 200 kg N per ha; bij hoge mineralisatiesnelheid gebeurde dit reeds bij stikstofgiften hoger dan 100 kg N per ha. Deze ophoping was op zware gronden iets groter dan op lichte gronden. De ophoping van minerale bodemstikstof aan het eind van het seizoen kan worden beschouwd als een stikstofverlies, omdat deze stikstof in de herfst en winter kan uitspoelen. Wanneer de huidige stikstofbemestingsadviezen voor aardappelen met 25 % zouden worden verlaagd, zoals voorgesteld is in hoofdstuk 4, zou onder normale omstandigheden het totale verlies door uitspoeling in het voorjaar en ophoping aan het eind van het seizoen niet tot gevolg hebben dat de EG-norm voor de maximaal toelaatbare nitraatconcentratie in drinkwater overschreden wordt. Het is dan ook niet te verwachten dat maatregelen, die het verder terugdringen van de stikstofgiften beogen, een ander effect zullen hebben dan verlaging van het inkomen van de boer (hoofdstuk 5). In die gevallen waarin de mineralisatiesnelheid veel hoger is dan normaal, worden veel te hoge stikstofgiften geadviseerd en zal het totale stikstofverlies meer dan 150 kg N per ha bedragen. Hierdoor zal de EG-norm voor de maximaal toelaatbare nitraatconcentratie in drinkwater overschreden worden.