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Development of nitrogen fertilizer recommendations for potatoes and sugar beet on the basis of soil testing

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Summary

Nitrogen response curves were used to describe yield as affected by various levels of nitrogen fertilization in a large number of trials with potatoes and sugar beet. It was found that the calculation of the optimum amount of fertilizer nitrogen depended on the choice of the response function and that the confidence intervals of the calculated optima were wide.

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, soil type and prior application of organic manures. The results of the statistical analysis were used to formulate recommendations for the use of nitrogen fertilizer in potato and sugar-beet production.

The performance of these recommendations was evaluated by applying nitrogen fertilizer retrospectively to the trials considered. It was found that, on average, an optimum fixed rate of fertilizer applied to all trials would not seriously affect yield as compared with a rate of fertilizer based on the mineral N content of the soil of each trial individually. However, as in the latter case less fertilizer nitrogen would be needed to obtain maximum yield, it is recommended to take the mineral nitrogen content of the soil into account. The recommendations could be further refined by taking into account in addition to the mineral nitrogen content of the soil in each trial individually, the effects of soil type and prior application of organic manures. However, this refinement of the recommendations did not improve their performance.

Introduction

To set up fertilizer recommendations based on soil testing, usually a large number of field experiments are conducted. In these experiments different levels of fertilizer are applied and crop yield is determined at each fertilizer level. Usually, in each experiment the optimum amount of fertilizer is estimated by using yield response functions. Next, the recommendations can be set up by relating the optimum supply of fertilizer to soil test values. In this paper data from experiments with potatoes and sugar beet are interpreted. From these experiments the effect of the choice of the response function is evaluated and attention is paid to the accuracy of determining the optimum application rate of fertilizer nitrogen as calculated for individual experiments. To obtain recommendations from the results of a group of fertilizer experiments, a procedure is suggested in which yield data of the group of experiments are combined and optima are assessed of the group of experiments, rather than analysing the experiments individually. Finally, the performance of the recommendations obtained is analysed. Parts of this paper were published earlier by *Neeteson* and *Wadman* (1987), *Neeteson* and *Zwetsloot* (1989) and *Neeteson* (1989).

Response functions used in fertilizer experiments

In **Table 1** a number of yield response functions to fertilizer input (x) are given. The first group is formed by the polynomials, of which the parabola is used very often. The following has been taken from *Mead* and *Pike* (1975): "The disadvantages of the polynomial as a response function are mainly those inherent in using a smoothing function with no biological justification. Extrapolation is not possible, because the form of the polynomial outside the range of x-values tested is not constrained by any prior knowledge. A specific disadvantage of the quadratic relationship is that it is symmetric about the optimum. Another disadvantage of the family of simple polynomials is that it does not include an asymptotic relationship." The linear and cubic polynomials are not very commonly used as fertilizer response functions and give problems with the interpretation of the data. Furthermore, modifications are used in which the x values are transformed by a root function. According to *Colwell* (1978) the second-order polynomial of the square root of x (Table 1) yields satisfactory results. The parameters from the polynomial functions can be assessed by using linear-regression analysis.

Table 1

Examples of mathematical expressions of yield response to fertilizer

Polynomials	
$y = a + b\,x$	line
$y = a + b\,x + c\,x^2$	parabola
$y = a + b\,x + c\,x^2 + d\,x^3$	cubic function
$y = a + b\,x^{0,5} + c\,x$	(*Colwell* 1978)
Exponentials	
$y = a + b \exp(c\,x)$	*Mitscherlich* function
$y = a + b \exp(c\,x) + d\,x$	(*Neeteson* and *Wadman* 1987)
Inverse polynomials	(*Nelder* 1966)
$y = (a + b\,x) / (1 + c\,x)$	linear-over-linear
$y = (a + b\,x) / (1 + c\,x + d\,x^2)$	linear-over-quadratic
$y = (a + b\,x + c\,x^2) / (1 + d\,x)$	quadratic-over-linear
Broken stick functions	
$y = a + b\,x$ when $x < x_0$ and $y = a + b\,x_0$ when $x_0 < x < x_1$ and $y = a + b\,x_0 + c\,(x - x_1)$ when $x > x_1$	

x: amount of fertilizer applied;
y: yield;
a, b, c, d, x_0 and x_1: parameters

The second group of functions is formed by the exponentials, of which especially the *Mitscherlich* function is well known. It should be possible to include in many experiments a descending part in the response curve at the higher fertilizer levels. For this purpose the *Mitscherlich* function can be modified by adding a linear term. To assess the values of the parameters of the exponential functions non-linear regression analysis has to be used. For this, many statistical packages are available nowadays. *Neeteson* and *Wadman* (1987) give an example of how non-linear regression analysis can be easily performed by using the modified exponential model by fixing the parameter c (Table 1) at a number of values.

The third group of response functions are the so-called inverse polynomials (*Nelder* 1966). These functions may imply non-linear regression analysis. The quadratic forms have a rising and a descending part.

The fourth group of response functions are formed by a number of broken-stick models and consist of two or more linear relationships (Table 1). In *Mead* and *Pike* (1975) it is stated that "Broken-stick models have been felt to be mathematically unsatisfying; fitting such models, while not complex, is not simply performed using standard programs, and it is at least arguable that discontinuities are not very realistic." However, in describing yield response to fertilizer input these models received more serious attention (*Boyd* et al. 1976).

To asses the response to fertilizer it is important that a sufficient number of levels of fertilizer are applied and that the range of levels is sufficiently wide. Ideally, the optimum would be in the centre of the range of fertilizer levels tested.

The experiments

The number of field experiments, and the distribution of the experiments over soil types and data on application of organic manures in the experiments are given in **Table 2.** Most of the potato experiments were performed

Table 2

Number of experiments at different combinations of soil type and kind of organic manure (*Neeteson* and *Zwetsloot* 1989)

Organic manures	Potatoes				Sugar beet			
	Sand	Loam	Clay	Total	Sand	Loam	Clay	Total
No organic manures	14	28	6	48	22	43	22	87
Green manures	2	15	7	24	2	26	18	46
Slurries	8	7	1	16	10	2	1	13
Green manures + slurries	1	5	4	10	2	1	1	4
Total	25	55	18	98	36	72	42	150

in the early eighties, and the sugar beet trials in the late seventies. They were performed all over the Netherlands. In each experiment different levels of fertilizer N were applied: 0, 100, 150, 200, 250, 300 and 400 kg N per ha in 3 blocks in the potato experiments. In the sugar beet experiments 6 levels ranging from 0 to 200 or 250 kg/ha were applied in 4 blocks. In the potato experiments fresh tuber yield was taken as the response variable. In the sugar-beet experiments it was root yield corrected for beet quality (*Neeteson* and *Wadman* 1987).

Calculations on single experiments

The results of calculations on single experiments were described by *Neeteson* and *Wadman* (1987). At first, the goodness of fit of the parabola was compared with that of the modified exponential model with fixed values for the coefficient c in the exponential term (Table 1). The calculations were done for each experiment individually. It was found that, in general, the modified exponential model resulted in a lower residual variance both for the potatoes and the sugar beet (**Table 3**). However, it should be recognized that in the modified exponential model the number of parameters were increased. Therefore, differences in mean squares between the two models became very small (Table 3). It was also found that the choice of model (parabola or modified exponential function) affected the frequency distribution of the calculated optima (**Figure 1**).

Table 3

Average residual sum of squares (RSS), degrees of freedom (DF) and residual mean squares (RMS) after fitting the quadratic and the modified exponential model (*Neeteson* and *Wadman* 1987)

Model	Potatoes			Sugar beet		
	RSS	DF	RMS	RSS	DF	RMS
Quadratic	206	18	11.4	358	21	17.0
Modified exponential	191	17	11.2	339	20	17.0

Further, the widths of the confidence intervals for the optima were assessed (*Neeteson* and *Wadman* 1987). They are indicative of the accuracy with which the optima could be estimated.

In the following the equations are given for the calculation of the economically optimum supply of fertilizer nitrogen as based on the parabola and the modified exponential model, respectively (for the meaning of parameters b, c, and d see Table 1; P: monetary ratio).

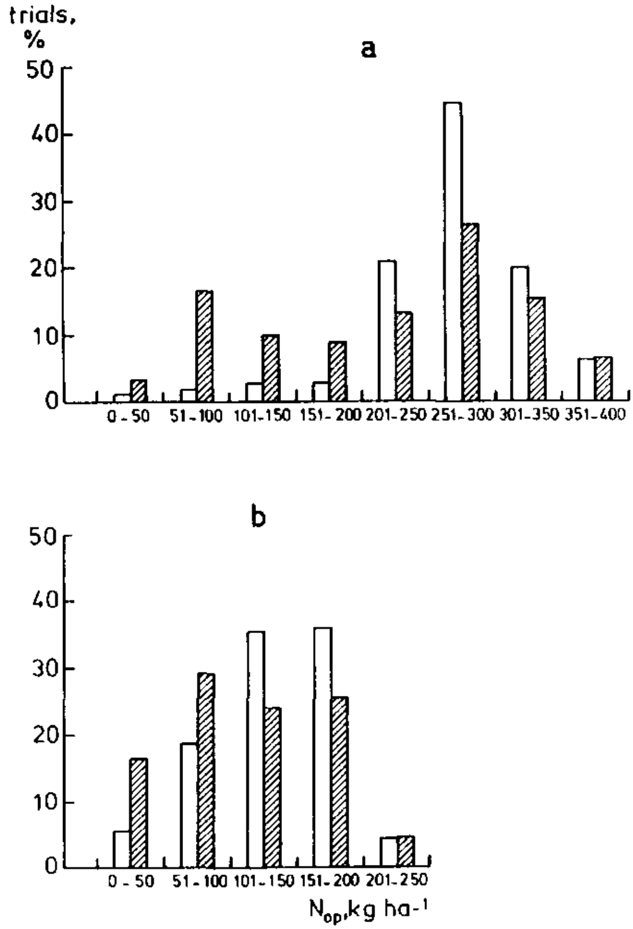
$$N_{op,\ parabola} = (P-b)/(2c) \quad (1)$$

$$N_{op,\ modified\ exponential\ model} = \ln\{(P-d)/(c\ d)\}/c \quad (2)$$

It is often impossible to accurately determine the parameters which arise in the denominator for calculating the optimum (equations 1 and 2). As they arise in the denominator and often do not significantly differ from zero or can be very close to zero, it is obvious that the confidence intervals may be wide, as dividing by zero leads to infinite values. This means that in individual experiments the optimum fertilization level could not be accurately assessed (*Neeteson* and *Wadman* 1987). Therefore, another method was used to assess crop response to fertilizer and to obtain fertilizer recommendations.

Figure 1

Optimum application rate of fertilizer N (N_{op}) for potatoes (a) and sugar beet (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) (*Neeteson* and *Wadman* 1987)



Calculations on a group of experiments

As was mentioned in the previous section, it was found that the often optimum supply of fertilizer N could not be determined accurately. Therefore, the various trials were combined for each crop by treating them as a large split-plot analysis of variance (*Neeteson* and *Zwetsloot* 1989). The yield data of all fields were combined. First, differences in yield level between fields and between blocks within fields were removed. In other words, the mean yield per block was made the same for all experiments, and also the mean yields of all experiments were made equal. It should be noted that the residual variance within the experiments differed between the experiments. This means that the variance is not homogeneous and has to be corrected before an analysis of variance can be performed. This was done by introducing a weighting factor for the residual variance for each experiment. This factor was taken to be equal to the inverse of the square root of the residual variance per experiment (*Neeteson* and *Zwetsloot* 1989).

The outcome of the analysis of variance of the potato trials is shown in **Table 4**. The stratum of interest is at the units level, that is at the level of interaction of fertilizer application and field and block to assess the factors responsible for differences in nitrogen response between fields. The table shows that a number of factors can be introduced. The models are numbered from 1 to 3 and become increasingly complicated. Model 1 states that yield response can be described by a *Mitscherlich* function in which only fertilizer input is considered and in which the response is the same on all fields. This is a very simple description. The table also shows that the use of model 2 increased the sum of squares. This model considers also N_{min} in the 0–30 cm layer. In this way various descriptions were used (*Neeteson* and *Zwetsloot* 1989). Finally, it was found that the best fit occurred by using

Table 4
Analysis of variance of the 98 potato trials (*Neeteson* and *Zwetsloot* 1989)

Source of variation	Sum of squares	Degrees of freedom
Total	82,149	2,057
Trial stratum	58,878	97
Trial.block stratum	1,459	196
Trial.block.units stratum	21,812	1,764
Model (1) : $y = b_0 + b_1 \exp(a_1 N_f)$	11,878	2
Model (2) : $y = b_0 + b_1 \exp(a_1 N_f + a_2 N_{m\,0-30})$	12,640	3
Model (3) : $y = b_{0ij} + b_{1ij} \exp(a_{ij} N_t)$	13,082	17
Residual of Model (3)	8,730	1,747

N_f: fertilizer nitrogen;
N_t: $N_t = N_f + 0.67\, N_{m\,0-30} + 0.33\, N_{m\,30-60}$;
$N_{m\,0-30}$: mineral nitrogen in the 0–30 cm soil layer;
$N_{m\,30-60}$: mineral nitrogen in the 30–60 cm soil layer;
b_{0ij}, b_{1ij}, a_{ij}, b_0, b_1, a_1 and a_2: parameters;
i: index for soil type (sand, clay or loam);
j: index for organic manuring (yes or no)

model 3. In this model it is assumed that yield response of potatoes is described by a *Mitscherlich* function of N_t in which, in addition to the N given as fertilizer, also N_{min} is taken into account. N_t is calculated as the weighted sum of N_{min} and fertilizer N according to the equation as given in Table 4. The coefficients of this equation were found from optimization of parameters.

Yield response significantly depended on soil type and on the application of organic manures (referred to as the indexes i and j in Table 4). Going from model 1 to model 3 the sum of squares is significantly improved, but the improvement of 1,204 (13,082–11,878) ist not very substantial as compared with the sum of squares of the trial.block.unit.stratum or the total variance. Still a large part of the variance is not accounted for.

The same procedure was followed in the sugar beet experiments. The results were similar. Again the most complicated model (model 3) was the best (**Table 5**). Now yield response was described by a modified exponential function of N_t, that is the *Mitscherlich* function with a linear term, to allow for decreasing yields at fertilizer levels which are higher than the level for maximum yield. Again, N_t was calculated as the weighted sum of N_{min} and fertilizer N (Table 5). This summation differs from the one in the potato trials (compare the equations for calculating N_t in Tables 4 and 5).

Table 5

Analysis of variance of the 150 sugar beet trials

(*Neeteson* and *Zwetsloot* 1989)

Source of variation	Sum of squares	Degrees of freedom
Total	156,470	3,599
Trial stratum	117,347	149
Trial.block stratum	3,186	450
Trial.block.units stratum	35,937	3,000
Model (1) : $y = b_0 + b_1 \exp(a_1 N_f) + c_1 N_f$	12,115	3
Model (2) : $y = b_0 + b_1 \exp(a_1 N_f + a_2 N_{m\,0-30})$ $+ c_1 N_f + c_2 N_{m0-30}$	15,856	5
Model (3) : $y = b_{0ij} + b_{1ij} \exp(a_{ij} N_t) + c_{ij} N_t$	17,579	23
Residual of Model (3)	18,358	2,977

N_f: fertilizer nitrogen;
N_t: $N_t = N_f + 0.82\, N_{m\,0-30} + 1.0\, N_{m\,30-60}$;
$N_{m\,0-30}$: mineral nitrogen in the 0–30 cm soil layer;
$N_{m\,30-60}$: mineral nitrogen in the 30–60 cm soil layer;
b_{0ij}, b_{1ij}, a_{ij}, b_0, b_1, a_1, a_2, c_1 and c_2: parameters;
i: index for soil type (sand, clay or loam);
j: index for organic manuring (yes or no)

From the parameters estimated by the analysis of variance as performed in Tables 4 and 5 the optimum amounts of N_t were calculated (**Table 6**). To obtain the economically maximum yield the most N_t was needed on the sandy soils without organic manures both for the potato and sugar-beet trials. The clay soils with organic manures required the least N_t to obtain the economically maximum yield. A lower value of optimum N_t in the trials with organic manures suggests that a higher rate of mineralisation took place in these trials than in the trials without organic manures and furthermore, the mineral N content of the soil does not completely reflect this difference in mineralisation rate.

Table 6

Economically optimum nitrogen requirement (weighted sum of fertilizer N and soil mineral nitrogen according to the equations in Tables 4 and 5) of potatoes and sugar beet, respectively, as affected by soil type and application of organic manures. The 90 % confidence interval for the optima is given in parentheses (*Neeteson* and *Zwetsloot* 1989)

Soil type	Organic manures	Optimum nitrogen requirement (kg/ha) Potatoes	Sugar beet
Sand	no	410 (356–486)	205 (192–235)
	yes	370 (280–467)	153 (136–172)
Loam	no	320 (294–351)	176 (170–183)
	yes	265 (236–307)	165 (155–171)
Clay	no	306 (254–388)	180 (172–193)
	yes	295 (265–353)	142 (134–158)

Performance of recommendations

In the Netherlands, fertilizer-N recommendations for potatoes and sugar beet are based on the N_{min} content of the soil (REC B in **Table 7**). The analysis as performed in the previous section would lead to recommendations differing from the current ones (REC C in Table 7). In addition to N_{min}, REC C also takes prior application of organic manures and the soil type into account. The latter two are accounted for by adding or subtracting a fixed value to or from a recommendation based on N_{min} alone. In addition to the current recommendations and the recommendations obtained in the previous section a fixed rate (calculated after optimization) was recommended (REC A in Table 7). The effect of choice of recommendation (REC A, B or C in Table 7) was evaluated by applying fertilizer N retrospectively to the trials mentioned in Table 2 (*Neeteson* 1989).

It was found that, on average, recommendations based on N_{min} would lead to lower applications of fertilizer N as compared with the fixed-rate method (Table 7). However, when yields are considered, differences are only small. The small differences can be explained by the shape of the response curves; there is a large segment in which yield is little affected by rate of fertilizer application. However, it was found that, compared with the other methods, the fixed-rate method for sugar beet carried a greater risk of obtaining yield deficits exceeding 5 % of the yield obtained at the measured optimum application rate of fertilizer nitrogen (*Neeteson* 1989).

Finally, the recovery of fertilizer N at the optimum fertilization level was examined in the trials with potatoes. Recovery is defined here as the part of the fertilizer N taken up by the tubers of the potato crop. The recovery was slightly affected by the recommendation method (**Table 8**).

Table 7

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

Recommendation	Soil type(s)	Organic manures	N_{rec}
Potatoes			
REC A	sand, loam, clay	no, yes	286
REC B[i]	sand	no, yes	$350-1.8\,N_{m\,0-30}$
	loam, clay	no, yes	$320-1.1\,N_{m\,0-60}$
REC C	sand	no	$410-0.7\,N_{m\,0-30}-0.3\,N_{m\,30-60}$
		yes	$370-0.7\,N_{m\,0-30}-0.3\,N_{m\,30-60}$
	loam	no	$320-0.7\,N_{m\,0-30}-0.3\,N_{m\,30-60}$
		yes	$265-0.7\,N_{m\,0-30}-0.3\,N_{m\,30-60}$
	clay	no	$305-0.7\,N_{m\,0-30}-0.3\,N_{m\,30-60}$
		yes	$295-0.7\,N_{m\,0-30}-0.3\,N_{m\,30-60}$
Sugar beet			
REC A	sand, loam, clay	no, yes	126
REC B[i]	sand, loam, clay	no, yes[1]	$200-1.7\,N_{m\,0-60}$[2]
		green manures	$170-1.7\,N_{m\,0-60}$
REC C	sand	no	$205-0.8\,N_{m\,0-30}-N_{m\,30-60}$
		yes	$155-0.8\,N_{m\,0-30}-N_{m\,30-60}$
	loam	no	$175-0.8\,N_{m\,0-30}-N_{m\,30-60}$
		yes	$165-0.8\,N_{m\,0-30}-N_{m\,30-60}$
	clay	no	$180-0.8\,N_{m\,0-30}-N_{m\,30-60}$
		yes	$140-0.8\,N_{m\,0-30}-N_{m\,30-60}$

[i]: The recommendations differ from the "official" guidelines in such a way that they are corrected for the current monetary ratios;
[1] With the exception of green manures;
[2] When $N_{m\,0-60}$ is 100–150, N_{rec} is fixed at 30; when $N_{m\,0-60} > 150$, $N_{rec} = 0$;
[3] When $N_{m\,0-60}$ is 85–135, N_{rec} is fixed at 30; when $N_{m\,0-60} > 135$, $N_{rec} = 0$.

Table 8

Recommended fertilizer nitrogen rate (N_{rec}) and yield of potatoes and sugar beet, respectively, and fertilizer nitrogen recovery by potatoes when different recommendation methods are used. Standard errors are given in parentheses (*Neeteson* 1989)

Recommendation	Potatoes			Sugar beet	
	N_{rec} (kg/ha)	Tuber yield[b] (t/ha)	N-recovery (%)	N_{rec} (kg/ha)	Root yield[c] (t/ha)
REC A[a]	286 (-)	56.9 (0.87)	31 (1.3)	126 (-)	63.7 (0.86)
REC B[a]	257 (5.1)	56.8 (0.88)	33 (1.1)	98 (3.8)	63.8 (0.89)
REC C[a]	288 (5.5)	57.0 (0.88)	31 (1.1)	120 (3.1)	64.1 (0.86)

a: See Table 7; b: fresh tuber yield; c: fresh yield, adjusted for beet quality

It may be concluded that the yields obtained with the fixed-rate method are only slightly different from those obtained when using the recommendations based on N_{min}. But because the recommendations based on N_{min} are lower, they should be preferred to the fixed-rate method. The results obtained with the current method differ little from those of the more refined method in which also soil type and prior application of organic manures are taken into account. Therefore, it does not appear to be necessary to change the current recommendations.

Conclusions

1. A number of yield response functions can be used to describe yield response to fertilizer.
2. The choice of the response function affects the calculated optima.
3. In the experiments described a high residual variance is observed.
4. It was preferred to combine the results of the fertilizer experiments and then use yield response functions rather than to characterize yield response by optima calculated from the data of individual experiments.
5. The recommendations remain rather crude, and cannot really be seen as field-specific. More field-specific factors should be introduced. Probably the most important factor is the rate of mineralisation.

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