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Nitrogen effects in sugar beet growing: a module for decision support

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Abstract

PIEteR is a field-specific production model for sugar beet growing in The Netherlands, developed as a basis for decision support, for example in nitrogen fertilization. Root and sugar yields, sugar content, (K + Na) and α-amino-N contents, extractability index, operating receipts (a measure for financial returns) and residual nitrogen in leaves were modelled as functions of nitrogen availability, defined as (N-fertilizer rate + $N_{min,\ 0\text{-}60\ cm}$ (soil, February)), and included in PIEteR as a so-called 'N-module'.

Analysis of experimental data showed that root and sugar yield were optimal at 240 and 200 kg N ha^{-1}, respectively. Sugar content and extractability index decreased, and (K + Na) and α-amino-N contents and fresh leaf yield increased with increasing N-availability. The operating receipts were optimal with 180 kg ha^{-1}, or with a nitrogen fertilizer rate of 130 kg ha^{-1}, assuming an N_{min}-amount in soil in February of 50 kg ha^{-1}. The results of the analysis were the basis for the functions in the N-module.

In an independent test on data of 100 fields, the prediction errors for root and sugar yields and financial result decreased by about 2% and the explained variances increased by about 15% by including the N-module.

Keywords: decision support, nitrogen fertilization, simulation model, sugar beet, *Beta vulgaris* L.

Introduction

The production model PIEteR [1] has been developed as a basis for a decision support system in sugar beet (*Beta vulgaris* L.) growing in The Netherlands. It predicts root and sugar yields, from which sugar content is calculated, (K + Na) and α-amino-N contents, from which the extractability index is calculated, and the operating receipts [2]

[1] PIEteR means: 'Production model for sugar beet, including Interactions between Environment and growing decisions, and their influence on the quantitative, qualitative and financial Result'.
[2] A measure for financial returns; more information is given in footnote 3 of Table 1.

which are calculated from the relevant yield and quality parameters (Smit & Struik, 1995; Smit *et al.*, 1995).

Two of the main decisions in sugar beet growing concern plant density and N-fertilization rate. In another paper we focused on the effects of plant density (Smit *et al.*, 1995). In that paper we hypothesised and proved absence of interaction between nitrogen availability and plant density. In the current paper N-fertilization is discussed, which has major effects on both yield and internal quality (Oltmann *et al.*, 1984; Van der Beek & Huijbregts, 1986). When the element N is short in supply, yield may be drastically reduced (Draycott, 1993). Nitrogen fertilizer usually depresses sugar content and juice purity (Van Burg *et al.*, 1983). With increasing N-rates more α-amino acids are produced and more Na^+- and (in most soils) K^+-ions are taken up by the roots; these ions accompany the accumulation of NO_3^--ions, keeping the anion-cation ratio balanced (Van Egmond, 1975). α-Amino acids and Na^+- and K^+-ions all reduce sugar beet quality, meaning that the percentage of sugar that can be extracted, decreases. To neutralize the acidifying α-amino-N compounds, NaOH is added; Na^+- and K^+-ions associate with sucrose-ions to non-extractable compounds (Jorritsma, 1985).

Chances that part of the minerals available in the root zone is lost during or after the growing season, are greater for N than for other elements such as P and K. Losses result mainly from leaching, denitrification and ammonia emission, partly leading to contamination of drinking water and air, respectively (Draycott, 1993; Olsson & Bramstorp, 1994). In our analysis of effects of N-fertilization on environment in this paper we focus on the amount of N_{min} which is found in the soil profile 0–60 cm and on the amount of (mainly organic) N in the crop residues immediately after harvest. Neeteson & Ehlert (1989) observed mean amounts of about 30 kg ha^{-1} and 100 kg ha^{-1} respectively with normal N-levels; even with very high N-levels only 40 kg ha^{-1} was found in the soil profile and 150 kg ha^{-1} in the crop residues (P. Wilting, pers. comm.).

The aim of our study was to produce an N-module which would be a simple and solid basis for decision support in sugar beet growing, not to fully understand and describe the N-balance in sugar beet growing. After a preliminary analysis of literature and data we decided to define 'nitrogen availability' and to describe the effects of mineral nitrogen fertilization on yield, quality, operating receipts and remaining N in crop residues, not taking into account the dynamics of processes leading to extra N available (mineralization) or N-losses (leaching, denitrification). Organic N fertilization was not considered in this study.

Materials and methods

Relevant equations

In this paper, the extractability index is calculated according to Van Geijn *et al.* (1983):

$$\text{Extr} = 100 - (0.342 * (\text{K} + \text{Na}) + 0.513 * (\alpha\text{N} - 17)) \quad (1)$$

in which

Extr	=	Extractability index of sugar beet (according to Van Geijn *et al.*)	[-]
K	=	K content	[mmol (100 g sugar)$^{-1}$]
Na	=	Na content	[mmol (100 g sugar)$^{-1}$]
αN	=	α-amino-N content	[mmol (100 g sugar)$^{-1}$]
100	=	Value of Extr if impurities are absent	[-]
0.342	=	The amount of sugar per unit K+Na lost in molasses [3]	[g (mmol K+Na)$^{-1}$]
0.513	=	The amount of sugar per unit α-amino-N lost in molasses [4]	[g (mmol α-amino-N)$^{-1}$]

The minimum value of α-amino-N content in the equation is 17 mmol (100 g sugar)$^{-1}$. Note that impurities are expressed on the basis of 100 g sugar and not on the basis of fresh weight of the beet.

Nitrogen availability is defined as:

$$\text{N-available} = N_{min,\,0\text{–}60\,cm} + \text{N-fertilization} \tag{2}$$

in which:

N-available	=	Amount of mineral N ($NH_4^+ + NO_3^-$), which is available after fertilization	[kg ha^{-1}]
$N_{min,\,0\text{–}60\,cm}$	=	Amount of mineral N, assessed in February in the soil layer 0-60 cm	[kg ha^{-1}]
N-fertilization	=	Amount of N, applied in February-April as mineral fertilizer	[kg ha^{-1}]

The recommended N-fertilization rate for sugar beet crops on Dutch clay, loess and sandy soils is given in Equation 3, aiming for the financial optimum (but not including costs of nitrogen fertilizer itself; Draycott, 1993; Neeteson & Smilde, 1983):

$$\text{N-fertilization} = 220 - 1.7 * N_{min,\,0\text{–}60\,cm} \tag{3}$$

in which:

N-fertilization	=	Amount of N, applied in February-April as mineral fertilizer or as manure with a comparable release	[kg ha^{-1}]
$N_{min,\,0\text{–}60\,cm}$	=	Amount of mineral N, assessed in February in the soil layer 0–60 cm (partly as a result of earlier manure applications)	[kg ha^{-1}]

The crop takes up more than the available amount of N in the soil layer 0–60 cm in February; the factor '1.7' is partly explained as mineralization during the growing season and uptake from deeper soil layers (Smit & Van der Werf, 1992). Equation 3

[3] 1 mmol of K+Na is accompanied by 1 mmol (or 0.342 g) of sugar.

[4] 1 mmol of α-amino-N (above the limit of 17 mmol (100 g sugar)$^{-1}$) is accompanied by 1.5 mmol sugar.

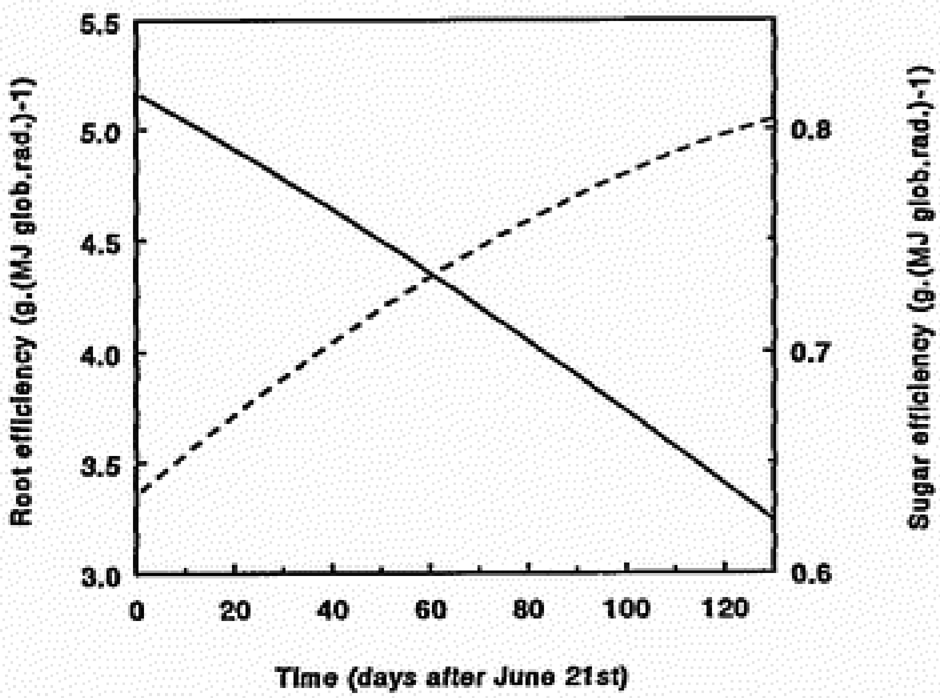


Figure 1 Development over time (after GPD) of the efficiency of fresh root and sugar production. (——: root; - - - : sugar)

does not describe the effects of a non-optimal N-level on yield and quality as required in a decision support system. Therefore, relationships between N-available on the one hand and yield, quality, environmental and financial parameters on the other had to be derived.

The model

In PIEteR, the growing season is divided into three phases: the emergence phase, the phase between emergence and canopy closure and the production phase (Smit & Struik, 1995). In the first two phases, temperature is regarded as the main determining factor for emergence and leaf formation rates; in the third phase, root and sugar production rates are mainly determined by the daily amount of global radiation. Light use efficiency functions play an important role in the translation of radiation levels into root and sugar production. These functions depend on the time after GPD [5], as shown in Figure 1. A soil moisture balance modifies the respective rates in every phase.

The derived functions for relative root and sugar yield, sugar content, (K + Na) and α-amino-N contents and for absolute fresh leaf yield and N-amount in crop residues were included in PIEteR. The extractability index and the operating receipts were not directly modelled, but calculated from the respective yield and quality parameters. PIEteR is written in TURBO-PASCAL, version 6.

[5] GPD is the 'Growth Point Date', which nearly coincides with the day on which the canopy closes, i.e. leaves from adjacent rows touch. Details are given in Smit and Struik (1995).

Effects of nitrogen

The Dutch Sugar Beet Research Institute (IRS, Bergen op Zoom) carried out field experiments with different levels of N-fertilization in different years and regions in The Netherlands. Table 1 gives materials and methods and the resulting data, which included fresh root, sugar and (estimated) fresh leaf yields; sugar, (K + Na) and α-amino-N contents; and N_{min}-levels after harvest; these were analysed in relation to level of N-fertilization and N_{min} in different soil layers in February. After a first analysis it was decided to concentrate on relative parameters, i.e. to express yields and contents in average values per experiment [6], except for fresh leaf yield. To calculate the extractability index according to Van Geijn *et al.* (1983), the average values of root yield, sugar content, (K + Na) and α-amino-N contents in the calibration data set were used for the relative value of 100% (Table 1). The operating receipts were calculated, applying the sales system in Table 1 and using the average extractability index in the data set.

Third-order relationships between 'N-available' and different yield and quality parameters were derived with the non-linear estimation procedure 'NLIN' in SAS (Anonymous, 1988).

Different (unpublished) field experiments of the Department of Agronomy provided data on the N-content of roots, leaves (blades and petioles) and crowns of sugar

Table 1. Information on the data set used for calibration of relationships between N-level and different yield and quality parameters, included in an N-module of PIEteR.

Sources of data:

A IRS-data of 10 fields * 5 N-rates during the period 1990–1992 (Van der Beek & Wilting, 1994); we used the data of full width application above 50 kg N ha^{-1}.

B IRS-data of 107 fields * 6 N-rates during the period 1977-1979 (not published); materials and methods were the same as for A; only dates and sites were different, and row application was not studied.

More information on materials and methods applied by IRS is given by Anonymous (1989; the current paper also gives information for later years).

Average values for the combined data set were:

Root yield:	57.5 tonnes ha^{-1}
Sugar content:	17.0%
Fresh leaf yield [1]:	35.9 tonnes ha^{-1}
(K + Na) content:	33.2 mmol (100 g sugar)$^{-1}$
α-amino-N content:	15.8 mmol (100 g sugar)$^{-1}$
Extractability index [2]	87.6
Operating receipts [3]:	7.35 kfl ha^{-1}

[1] Given for most fields in data set B

[2] According to equation 1

[3] Sales system:
0.115 kfl (1 kfl = 1000 Dutch guilders) per net ton of sugar beets, corrected with 9% per percent sugar content above or under 16% and with 0.9% per point extractability index above or under 85; penalties for dirt tare were not included in our calculations. This system was used in 1993 by Suiker Unie, one of the sugar beet processing companies in The Netherlands (Menu, 1993).

[6] An experiment is here defined as a set of N-applications at one field and in one year.

beets at different N-rates and at different soil types. Methods and materials of the applied N-analysis are given by Walinga *et al.* (1989). In one of these experiments (in 1993) we applied three levels of N-fertilization in four replicates: 0, 100 and 200 kg N ha^{-1}, whereas $N_{min, February}$ was 50 kg ha^{-1}.

Total N-amounts in crop residues were modelled by combining the fresh leaf and crown yields with their respective N-contents. We had only data on crowns from the 1993 field experiment, so that the simulations for crown yield and crown N content could not be validated.

Tests

Root and sugar yields, sugar content, extractability parameters and post-harvest N-levels in crop residues were predicted with and without corrections for available N. In addition, the operating receipts per ha were calculated in order to evaluate the integrated effect of the N-module on the quality of farm economic predictions as a basis for decision support.

In the test, an independent data set consisting of results from 100 (experimental) fields was used; 96 of these contained a complete set of IRS-trials on N-supply on Dutch clay, sandy and reclaimed peat soils in the period 1980-1982; only a few fields with 'abnormal' split applications of nitrogen were not taken into account. Those that received a supply at a normally recommended level have already been described by Smit & Struik (1995). Four fields were located at the Experimental Station for Arable Farming and Field Vegetable Production (PAGV), Lelystad, yielding data of fields on clay soil which were accurately sampled for modelling purposes during 1978 and 1981-1983. Additional information is given in Table 2.

The prediction error, the absolute difference between observed and predicted values, was calculated for every variable and every field, expressed in units and as percentages of the observed value, and averaged over all fields included. In addition, linear regression analysis was applied to test how well the predicted values matched the observed ones. We used the explained variance (R^2) as a measure.

Besides the values at final harvest, the (K + Na) and α-amino-N contents and extractability indices during the season were studied. The applied version of PIEteR included effects of plant density as well, described by Smit *et al.* (1995).

Results

The model

Figures 2A-2B show the relationships between available nitrogen and relative yield, quality and financial parameters, derived from the fields described in Table 1. We assumed that these fields represented The Netherlands as a whole. Root and sugar yields were optimal at 240 and 200 kg N ha^{-1}, respectively. When the N-rate increased by 15 kg ha^{-1} over the N-availability range 100-250 kg ha^{-1}, the sugar content and the extractability index decreased by 0.08% and 1.9 units respectively, and

Table 2. Test results of PIEteR over 100 fields, with and without correction for N-availability (N-available = $N_{min, February} + N_{fertilizer}$).

Test [1]	Var. [2]	Results		Mean prediction error		Explained variance
		Observed	Simulated	(kg m^{-2},%, mmol,kfl)	(%)	(R^2,%)
1	root	6.13	6.30	0.78	14.9	40.4
2	root	6.13	6.31	0.75	14.1	43.2
3	root	6.13	6.27	0.67	11.5	60.4
1	sugar	1.04	1.07	0.12	13.9	45.7
2	sugar	1.04	1.06	0.11	12.6	51.9
3	sugar	1.04	1.06	0.11	10.9	64.7
1	s.cont	16.9	16.9	0.7	4.0	4.0
2	s.cont	16.9	16.8	0.7	3.9	8.6
3	s.cont	16.9	16.9	0.5	3.1	31.6
1	K+Na	29.51	34.19	6.05	21.7	42.1
2	K+Na	29.51	33.36	5.37	19.1	48.7
3	K+Na	29.51	33.15	5.19	18.3	50.7
1	αN	12.49	13.76	4.76	48.0	0.1
2	αN	12.49	13.19	4.49	44.0	0.2
3	αN	12.49	12.82	3.13	26.8	40.0
1	Extr	89.5	88.2	2.4	2.7	26.7
2	Extr	89.5	88.5	2.1	2.4	28.9
3	Extr	89.5	88.4	2.1	2.5	45.1
3	Leaf	3.67	3.45	0.61	17.1	53.6
3	N-leaf	85.8	91.8	23.8	40.4	44.1
1	Pay	7.81	7.99	0.94	13.6	40.5
2	Pay	7.81	7.96	0.86	12.2	50.1
3	Pay	7.81	7.94	0.76	10.3	63.9

[1] 1 = without corrections for plant density and N-availability
2 = with corrections for plant density, but not for N-availability
3 = with corrections for both plant density and N-availability

Additional information over 100 fields:

– Average sowing date:	day 98 (8 April)
– Average simulated GPD:	day 175 (24 June)
– Average plant density (spring):	7.6 plants m^{-2}
– Average amount of N in soil layer 0–60 cm (February):	51 kg ha^{-1}
– Average level of N-fertilization:	127 kg ha^{-1}.

[2]

'root'	= fresh root yield	[kg m^{-2}]
'sugar'	= sugar yield	[kg m^{-2}]
's.cont'	= sugar content	[%]
'K+Na'	= (K + Na) content	[mmol (100 g sugar)$^{-1}$]
'αN'	= α-amino-N content	[mmol (100 g sugar)$^{-1}$]
'Extr'	= extractability index	[–]
'Leaf'	= fresh leaf yield	[kg m^{-2}]
'N-leaf'	= Amount of N in leaves	[kg ha^{-1}]
'Pay'	= Operating receipts [3]	[kfl ha^{-1}]

[3] The sales system is explained in footnote [3] of Table 1.

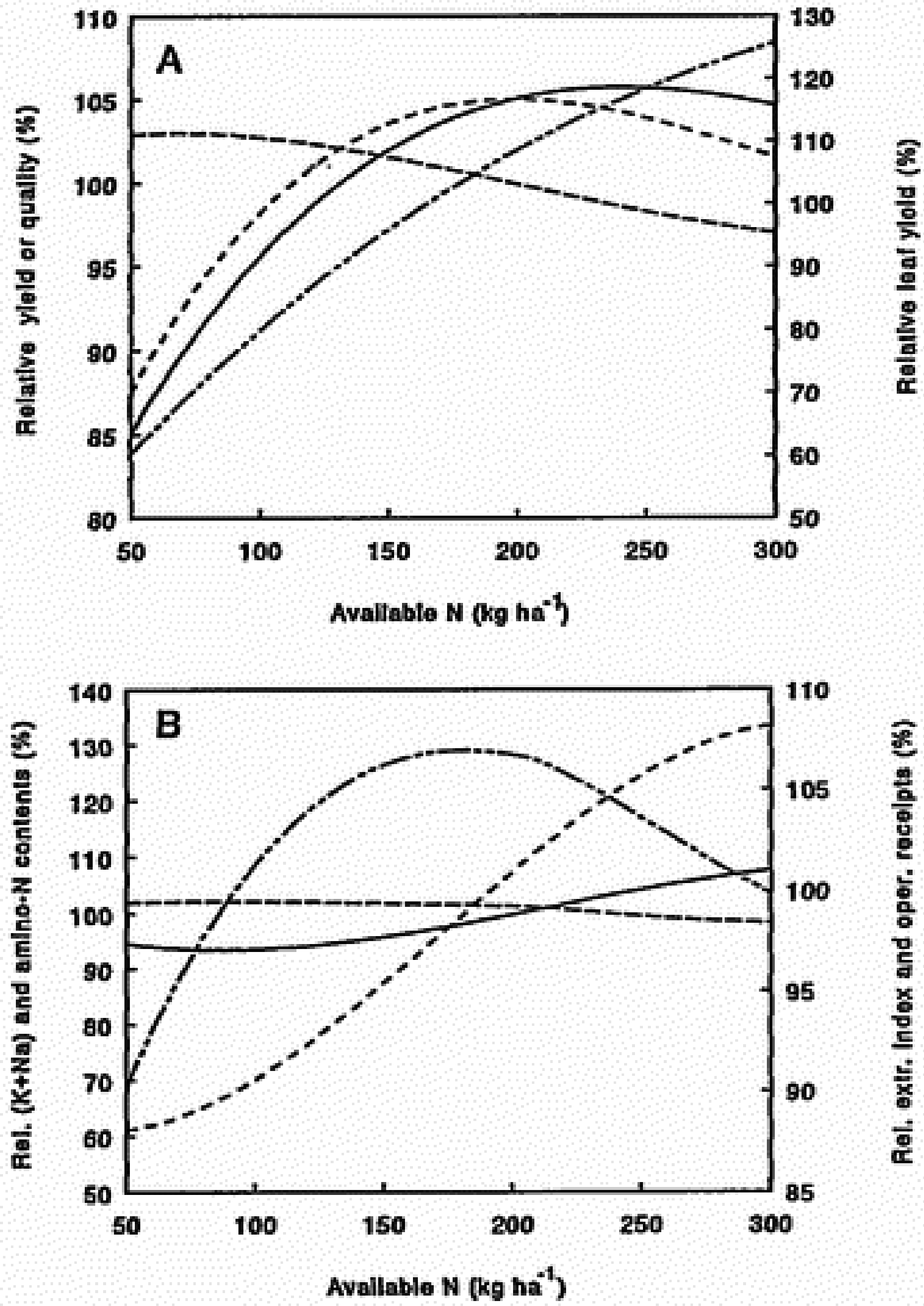


Figure 2. Relative yield, quality and financial parameters vs. available nitrogen (N-avail = $N_{min,\ February}$ + $N_{fertilizer}$). A: Root, leaf and sugar yield, and sugar content; the equation for fresh leaf yield is given for absolute values ('Abs. leaf', in tonnes ha^{-1}). Note that the equation describes absolute leaf yield (as included in the model), whereas the curve gives values relative to the means in the data set (root = 69.5 + 0.366 * N - 1.16E-3 * N^2 + 1.11E-6 * N^3 (R^2 = 62.3%); sugar = 70.0 + 0.424 * N – 1.61E-3 * N^2 + 1.83E-6 * N^3 (R^2 = 54.3%); sugar content = sugar/root * 100%; Abs. leaf yield = 12.8 + 0.183 * N – 3.23E-4 * N^2 + 1.92E-7 * N^3 (R^2 = 61.6%)); B: (K + Na) and α-amino-N contents, extractability index (according to Van Geijn *et al.*, 1983), and operating receipts (receipts: according to footnote 3, Table 1; K + Na = 100 – 0.169 * N + 1.21E-3 * N^2 – 1.88E-6 * N^3 (R^2 = 49.9%); αN = 65.5 – 0.260 * N + 3.80E-3 * N^2 – 7.27E-6 * N^3 (R^2 = 72.9%)). (A: ——: root yield; – – –: sugar yield; — — —: sugar content; — - — - —: leaf yield; B: ——: (K + Na) content; - - -: α-amino-N content; ———: extractability index; — - — - —: operating receipts).

the (K + Na) and α-amino-N contents increased by 0.35 and 0.83 mmol (100 g sugar)$^{-1}$ respectively, assuming average values of 17%, 87.6 and 33.2 and 15.2 mmol (100 g sugar)$^{-1}$ respectively. The operating receipts were optimal at 180 kg ha^{-1}. The shape of the curves for extractability and receipts changed beyond 215 kg ha^{-1} as a

Table 3. Observed and simulated results of plots with recommended N-rate [1] in a field experiment in Wageningen in 1993. The observed values are means of four replicates.

Parameter	Observed	Simulated
Fresh leaf yield (kg m^{-2})	3.8	3.6
Dry matter content leaves (%)	12.6	–
N content leaves (fresh basis, %)	0.30	0.30
Residual N-amount in leaves (kg ha^{-1})	114	109
Fresh crown yield (kg m^{-2})	0.88	–
Dry matter content crowns (%)	24.2	–
N content crowns (fresh basis, %)	0.24	–
Residual N-amount in crowns (kg ha^{-1})	21	21
Total residual N-amount in leaves and crowns (kg ha^{-1})	135	130

[1] N-fertilization rate = 100 kg ha^{-1}; $N_{min, February}$ = 50 kg ha^{-1}.

result of α-amino-contents exceeding the threshold value of 17 mmol (100 g sugar)$^{-1}$.

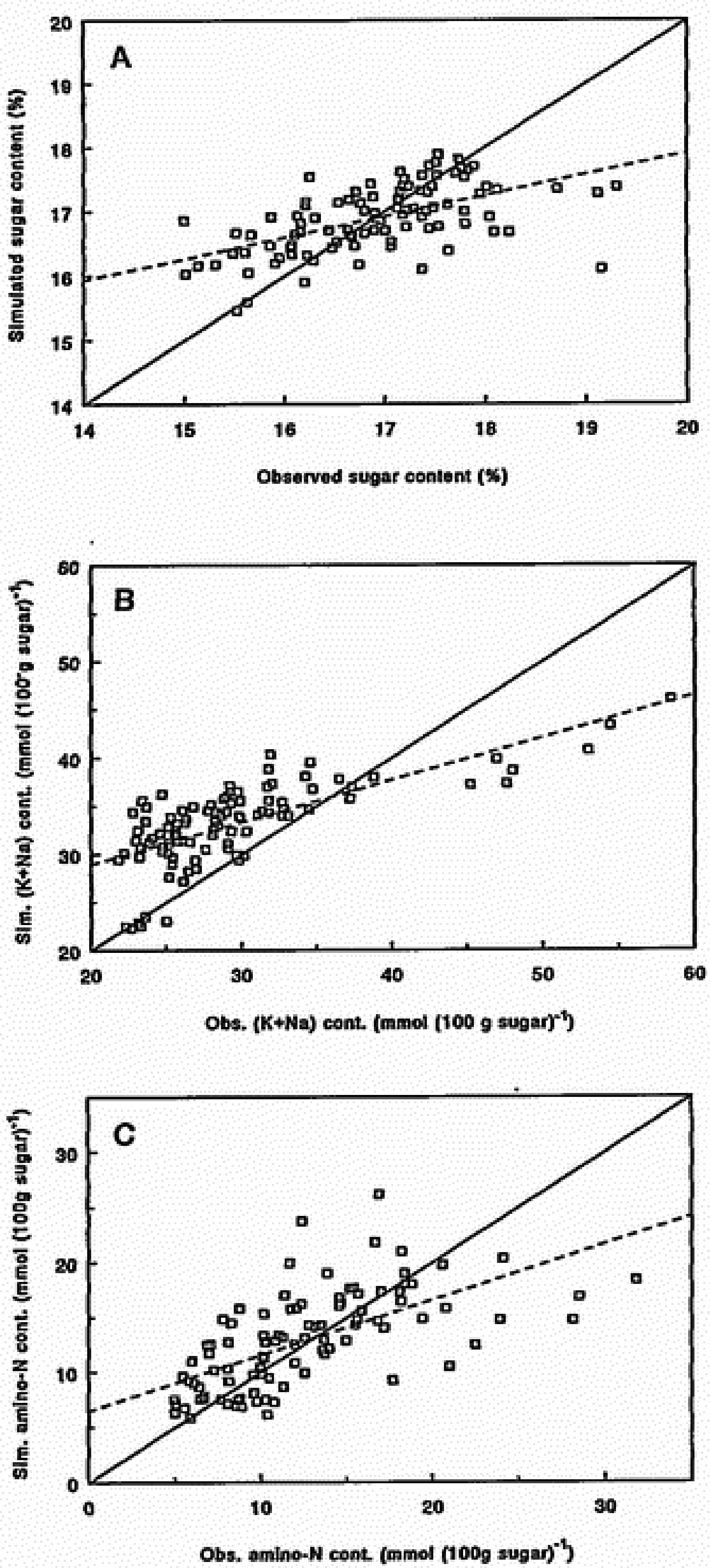
The amount of total N in crop residues immediately after harvest was calculated from the fresh leaf yield by assuming a nitrogen content of 0.30% for both sandy and clay soils (J. Vos and P. Van der Putten, pers. comm.). The amount of total nitrogen in crop residues increased with increasing N-availability, similarly to the fresh leaf yield. An analysis of the N-availability in February on the one hand and the post-harvest level of residual mineral N in the soil layer 0-60 cm on the other showed that there was no relationship between the two.

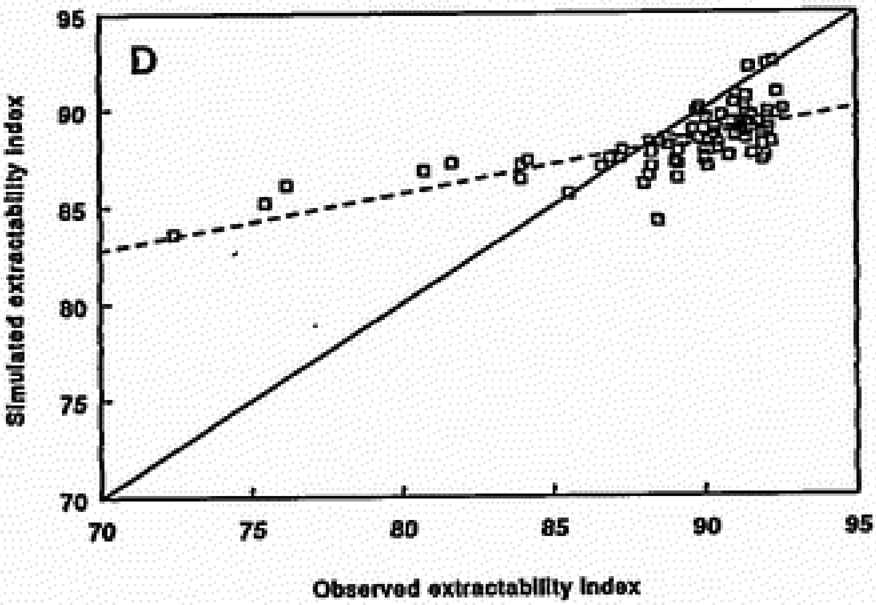
Some of the results of the 1993 field experiment for the plots with 100 kg ha^{-1} (close to the recommendation in Equation 3) are given in Table 3, including the simulated values for this experiment. We assumed and generalised that the amount of remaining N in crowns was linearly related to fresh root yield, which was 8.22 kg m^{-2} in this case.

Tests

The results of field specific simulations with and without N-correction are given in Table 2. When N-corrections were included in PIEteR the explained variance of all parameters increased. For root and sugar yields, sugar, (K + Na) and α-amino-N contents and operating receipts the mean prediction error decreased. The prediction error remained more or less constant in the case of extractability index.

Figures 3A-3E show that all parameters were overestimated at low values and underestimated at high values. Smit *et al.* (1995), using the same data set, showed that the integrating parameter, operating receipts, was overestimated in about 55% of the predictions. The predicted course of the quality parameters during the season was in some cases not very accurate, but the extractability index at final harvest had mean prediction errors of only 2.5%. Figures 4A-4B show the course for two fields with relatively poor and good simulation results. The prediction was better in the end of the growing season than in the beginning.


A
Simulated sugar content (%)
Observed sugar content (%)
B
Sim. (K+Na) cont. (mmol (100 g sugar)$^{-1}$)
Obs. (K+Na) cont. (mmol (100 g sugar)$^{-1}$)
C
Sim. amino-N cont. (mmol (100g sugar)$^{-1}$)
Obs. amino-N cont. (mmol (100g sugar)$^{-1}$)



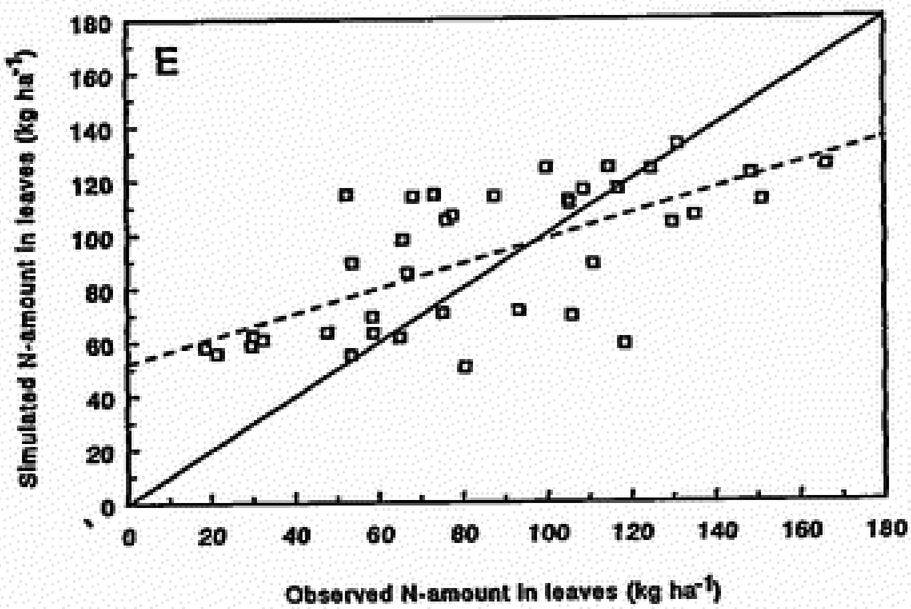


Figure 3. Simulated (with model PIEteR) vs. observed quality and environmental parameters. A: sugar content (n = 100; R^2 = 31.6%); B: (K + Na) content (n = 100; R^2 = 50.7%); C: α-amino-N content (n = 100; R^2 = 40.0%); D: extractability index (according to Van Geijn *et al.*, 1983; n = 100; R^2 = 45.1%); E: amount of total residual N in leaves (n = 38; R^2 = 44.1%).
(——: line Y = X; ... : Regression line)

Discussion

The model

According to Bosch (1986) the optimal N-rate for root and sugar production ranges from 120 to 160 kg ha^{-1}. Assuming an N-amount of 50 kg ha^{-1} in the soil layer 0–60 cm in February, the optimal N-availability ranges from 170 to 210 kg ha^{-1}. Van Burg *et al.* (1983) stated that the optimal N-level is always lower for financial returns than for root and sugar yields, being 180, 240 and 200 kg ha^{-1} in our analysis, respective-

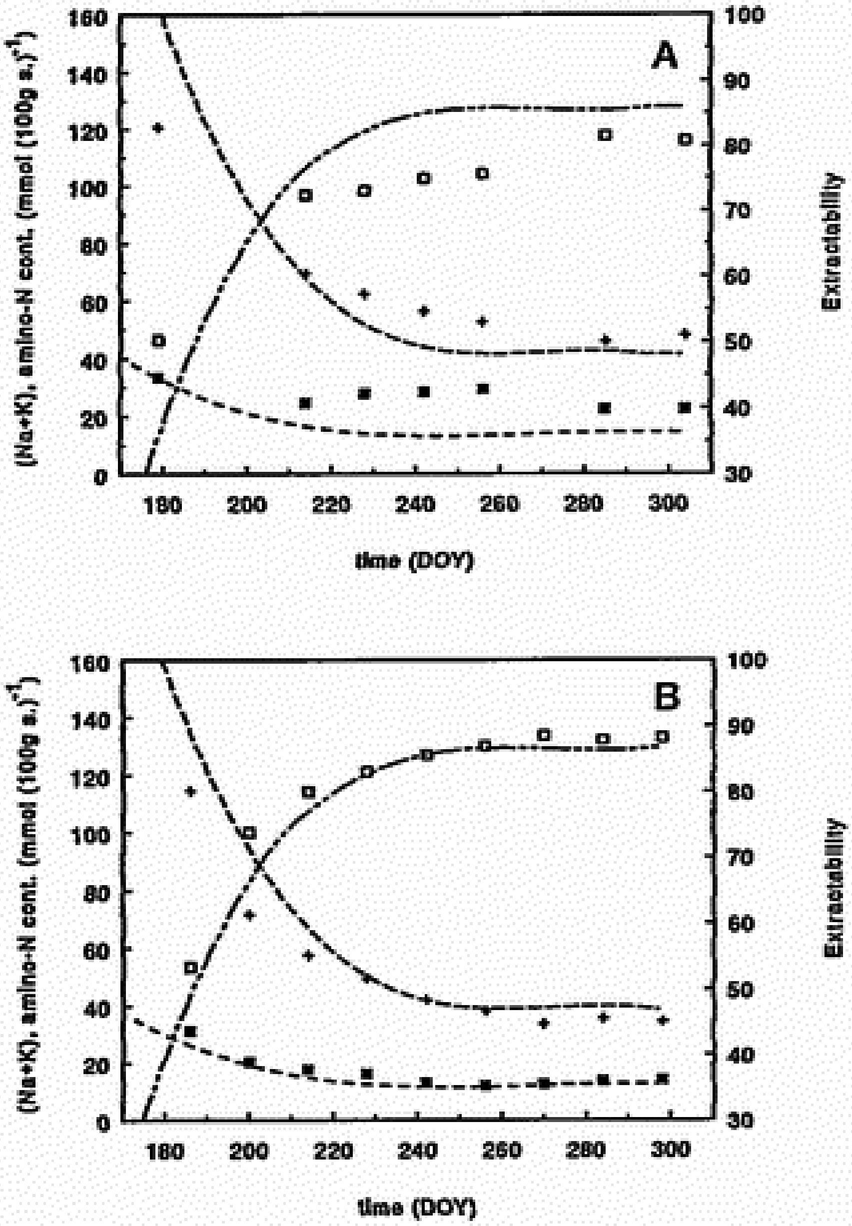


Figure 4. Observed and simulated (with model PIEteR) (K + Na) and α-amino-N contents and extractability index (according to Van Geijn *et al.*, 1983) vs. time. A: field with relatively poor simulation results; B: field with relatively good simulation results.
(+ : Observed (K + Na) content; ■ : Observed α-amino-N content; □ : Observed extractability index (according to Van Geijn *et al.*); ——— : Simulated (K + Na) content; - - - : Simulated α-amino-N content; - . . . - : Simulated extractability index)

ly. According to Last *et al.* (1994) the economic optimum in English trials was 128 kg N ha^{-1} on average.

Compared to our results, Bosch (1986), Van Burg *et al.* (1983) and P. Wilting (pers. comm.) reported similar values for sugar content decrease with increasing N-rates: 0.1%, 0.07% and 0.06-0.09% per 15 kg N ha^{-1}, respectively. Sugar content decreases with increasing nitrogen supply (until a certain limit) due to an increase of root cell size; there is no specific effect on sugar storage itself (Milford & Watson, 1971; Watson *et al.*, 1972), unless the absolute root fresh yield declines as well.

P. Wilting (pers. comm.) and Van der Beek (1991) found similar values as we did for the effects of N on the α-amino-N content and the extractability index. However,

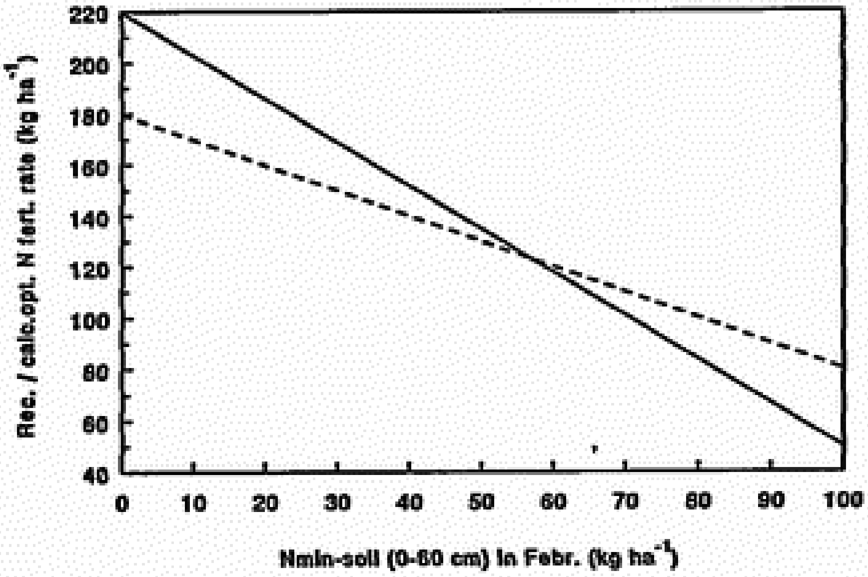


Figure 5. Recommended N-fertilizer rate vs. $N_{min, 0-60\ cm}$ according to the official recommendation in The Netherlands and calculated optimum from statistical analysis.
(——: Official recommendation; - - - : calculated optimum)

according to P. Wilting (pers. comm.) there is no uniform effect of nitrogen on the (K + Na) level; in certain soils, for example sandy and reclaimed peat soils in The Netherlands with low K contents (especially in deeper soil layers), the K content (in mmol (100 g sugar)$^{-1}$) does not significantly increase with increasing N-level.

Operating receipts were maximal when the N-availability was 180 kg ha^{-1}, or the N-fertilization rate 130 kg ha^{-1}. Applying Equation 3 the normally recommended rate would be 135 kg ha^{-1}, assuming 50 kg N_{min} ha^{-1}. The recommended N-rate according to Equation 3 is higher than our optimum for soil N-amounts less than 57 kg ha^{-1} and lower beyond 57 kg ha^{-1} (Figure 5). Costs of N-fertilizer were not taken into account in both calculations; correction for costs of fertilizer decreases the optimum N-rate by 20 kg ha^{-1} (P. Wilting, pers. comm.)[7]. Equation 3 is a rough estimate, because it does not take temperature, moisture content and type of soil into account, nor the use of organic manure in the past, all of them influencing the level of mineralization (Anonymous, 1991). In Belgium (N-index, Vandendriessche *et al.*, 1992) and France (N-balance, Viaux, 1981), the N-recommendation systems include N-mineralization, the use of organic manure in the past and factors with a negative influence on N-mineralization (e.g. pH and soil structure). The equation for Spanish N-recommendations contains a (negative, linear) factor for organic matter content of the soil, and irrigation and organic fertilization are also taken into account (Barbanti, 1994).

The dynamics of processes leading to N-supply (mineralization) or N-losses (leaching, denitrification) during the growing season were not taken into account in the model. Including these would probably improve the results of the N-module of PIEteR as well as the official recommendations; however, both processes are very difficult to model because of their complexity (De Willigen *et al.*, 1992). Neither

[7] Valid for the 1993 price ratio between sugar beet and fertilizer.

was attention paid to possible supply of N in organic form, although up to two thirds of the total amount of N required can be applied in this form on sugar beets (B. Ruiter, pers. comm.); manure application in spring is common on most sandy, reclaimed peat and loess soils in The Netherlands. N from organic sources needs more time to become available to the crop than fertilizer-N, which makes it rather difficult to assess the optimal amount of additional fertilizer-N. Nevertheless, the Dutch Nutrient Management Institute (NMI) has done an effort to optimize the use of animal manure and fertilizer in a so-called Integrated Fertilization Programme (Van Erp & Oenema, 1992).

The environmental consequences of N-fertilization were not studied in full detail, but we focused on the amounts of N which had been observed in the soil and in the crop residues immediately after harvest. We did not find any relationship between the N-availability in spring and the nitrogen level in the soil after harvest ($N_{min,\ 0\text{-}60\ cm,\ after\ harvest}$). Schröder *et al.* (1994) came to the same conclusion. In general, $N_{min,\ 0\text{-}60\ cm,\ after\ harvest}$ is relatively low; Baumgärtel & Engels (1994) and Van Erp & De Jager (1992) mentioned 40 kg ha^{-1} in the soil layer 0-90 cm on average. Within the normal N-application range of 0-200 kg ha^{-1}, a limit of 70 kg ha^{-1} in the soil layer 0–100 cm as proposed to the Dutch government will not be exceeded (Goossensen & Meeuwissen, 1990). An important research topic concerns the fate of the nitrogen in the crop residues. If it is mineralised during the winter, it may partly be lost through leaching. Van Erp *et al.* (1993) found that the C/N-ration of the residues is an important factor, which in turn is to a large extent determined by the weather conditions during the growing season, the amount of dry matter produced and the amount of mineral nitrogen available during the growing season. The date of incorporation of the residues is also important; the later this date, the smaller the risk that nitrogen is lost through leaching. Therefore, the proposed limit of 70 kg ha^{-1} will not be a guarantee that during winter time the nitrogen contents of the upper soil layers will stay low nor that leaching of nitrogen will be avoided.

Simulation of fresh leaf amount at harvest appeared to be a useful method to predict residual N in leaves. The type of harvester machinery and its fine tuning greatly influence the amount of leaf and crown removed. The amount of residual N in post-harvest crop remainders may therefore vary widely, making predictions very difficult. Since the residual N-amount in crowns is much smaller than in leaves, variation of cutting depth will be of minor influence on the total amount of residual N. Values mentioned by other authors are listed in Table 4.

According to Held *et al.* (1994) the farmer should adapt the N-fertilization rate to harvest date. With early harvest the N-rate should be lower than with late harvest. C.E. Westerdijk & J.J. Tick (pers. comm.) recommended a reduction of N-rate by 50 kg ha^{-1} to optimize quality in case of early harvest. Uptake of nitrogen in a final stage of the growing season reduces quality (Vandendriessche *et al.*, 1992). However, Huiskamp (1982) showed that there is no effect of harvest time on nitrogen requirement, and in official recommendations the IRS states that the N-rate is independent of harvest date (P. Wilting, pers. comm.). All N required is taken up before September. The N-content of the soil layer 0-60 cm in the first half of August should be less than 30 kg ha^{-1} to ensure a good quality at any harvest time (P. Wilting, pers.

Table 4. Yields of crop residues and total nitrogen contents of crop residues. Values at optimal N-fertilization from literature and experiment.

Reference	Dry yield crop residues ($kg\ m^{-2}$)	Fresh yield crop residues ($kg\ m^{-2}$)[1]	Total N-yield of crop residues ($kg\ ha^{-1}$)
Smit & Van der Werf (1992)	0.4	2.67	120
Van Erp & De Jager (1992)	0.55	3.67	127
De Willigen *et al.* (1992)	0.6	4.0	104
Van der Beek (1991)	–	–	120-150
Olssen & Bramstorp (1984)	–	–	100-160
Smit *et al.*, experiments	0.69	4.68	135
Smit *et al.*, model	–	–	130

[1] The fresh yield of crop residues was not given (except in our data set); it was calculated from dry yields by assuming a mean dry matter content of leaves and crowns of 15%.

comm.). Therefore, to exceed the earlier mentioned limit of 70 kg ha^{-1} over a depth of 100 cm (Goossensen & Meeuwissen, 1990) would be unfavourable for the quality of both environment and product. Redistribution from senescent leaves and mineralization will provide sufficient nitrogen after August 15th (Von Müller & Winner, 1980).

The influence of variety on the effects of N was not analysed. Wilting (1993) stated that there is no interaction between N-rate and variety, although the level of yield and quality can be very different for different varieties. Often varieties with high root yields have a relatively low quality and vice versa (Anonymous, 1993). The modelling of fresh leaf yield was based on data of varieties in the 1970's, which were relatively uniform in this aspect. In recent years varieties have become more diverse, also with respect to the fresh leaf yield. Nowadays fresh leaf yield varies between 40 and 75 tonnes ha^{-1} at maximum. After leaf maximum (normally at the end of August) fresh leaf yield may decrease to an extent which strongly varies with year (M.A. Van der Beek, pers. comm.). The question is whether a higher leaf yield corresponds with a lower N-content, making the post-harvest residual N-amount independent of variety, even with the current varieties. This interesting topic requires additional research.

We assumed that the N-content of leaves was independent of N-fertilization rate; however, from unpublished research data (H. Snijders, pers. comm.; F.A.R. Inghels & A.F.M. Jacobs, pers. comm.), it can be concluded that with increasing N-rate the accumulation of nitrogen in root and leaves increases more than the fresh root and leaf yields, resulting in an increase of the nitrogen content in the fresh matter. PIEteR probably overestimated the amount of residual N in leaves in case of low observed amounts, since the nitrogen content in the unpublished data was usually lower than 0.3%. More research is necessary to assess the exact relationship between N-availability and N-content of root and leaves.

Tests

N-corrections had more influence on the accuracy of PIEteR than plant density corrections (cf. Smit *et al.*, 1995). Compared to model predictions without N corrections and plant density corrections, the explained variance increased more and the prediction error decreased more through N-correction than through plant density correction for all parameters included except for the (K + Na) content.

One simulation result for sugar content was extremely poor (Fig. 2A). The observed and predicted sugar contents were 19.2% and 15.9% respectively. In 1983, sugar beet was sown late in the very fertile clay soil in Lelystad, because of large amounts of rainfall during spring. Because of a short growing season the ratio between simulated sugar and fresh root efficiency was relatively low (cf. Smit & Struik, 1995). The observed root yield was equal to the predicted root yield (5.6 kg m^{-2}), but the observed sugar yield was higher than the predicted sugar yield (1.1 vs. 0.9 kg m^{-2}). Apparently, the model was not able to correct sugar content for the combination of a late sowing date and a fertile soil.

The quality of sugar beets on soils with high amounts of N and/or K and/or Na at a level deeper than 60 cm and a deep rooting system may be lower than predicted on the basis of $N_{min,\ 0\text{–}60\ cm}$ in February (P. Wilting, pers. comm.). This was probably true for some of the tested fields, located in the newly reclaimed 'polders'; the observed (K + Na) and α-amino-N contents were much higher than the predicted ones and the extractability index much lower than the predicted one (Figures 3B-3D).

The work presented in this paper resulted in better predictions by PIEteR of yield, internal quality and financial returns for different N-levels. However, the test showed that PIEteR in general overestimated root yield and underestimated extractability index. As a result of the overruling influence of root yield on operating receipts, PIEteR overestimated the financial returns as well. Our aim of decision support requires higher explained variances, especially for root yield, sugar content and operating receipts, and regression equations that resemble Y = X more closely. However, the fields used in the tests had a larger variation in N-availability than usually observed in practice; the intersections of the Y = X and the regression lines were found in the normal ranges of sugar, (K + Na) and α-amino-N contents (Figures 3A-C), the extractability index (Figure 3D) and the operating receipts (Figure 2 in Smit *et al.*, 1995) on commercial fields. Compared to the version of PIEteR without N-module, we made considerable progress. Moreover, fresh leaf yield and total nitrogen content in crop residues were predicted, which will give the farmer insight into the effects of his decisions on environmental aspects of sugar beet growing. Thus, PIEteR was made more capable to support sugar beet growers' decisions by including the effects of N-availability.

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