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Modelling the response of crops to fertilizers

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Abstract

Relations between nutrient uptake and yield and the balance between nutrients form the basis of the presented model. The model calculates the yield of a crop as a function of the uptake of N, P, and K. For each nutrient a range of possible yields is calculated, and the yield ranges are combined to one yield estimate.

The actual uptake of a nutrient is calculated as a function of the potential supplies of all three nutrients. Several methods for the assessment of the potential supplies of nutrients are discussed. Once the supplies are known the effects of fertilizer application can be calculated. Fertilizers increase the potential supply but not necessarily the uptake of a nutrient. Setting prices for fertilizers, the most economic combinations can be found.

Introduction

In the course of some projects on soils and crops in Kenya and Suriname, a system has been developed for quantitative evaluation of the fertility of tropical soils (Janssen *et al.*, 1990). The principles of this so-called QUEFTS system can be applied also to calculate the response to fertilizers (Janssen *et al.*, 1989). The pivot of the system is formed by the relations between nutrient uptake and yield of maize. In principle, other nutrients than N, P and K can be included, provided the relationships between uptake of those nutrients and yield have been established. The methodology of the model can be used for each crop of which the relationships between nutrient uptake and the yield of the economic product are known.

Main concepts used in the system

Some of the concepts used in the model need an explanation: actual uptake and potential supply, maximum recovery fraction, maximum accumulation and maximum dilution of a nutrient in the crop.

In the soil, nutrients are made available to crops by processes like mineralization of organic matter and weathering of minerals. Often the supplies of the different nutrients are not in balance with the needs of a crop. When the supply of a particular nutrient is small compared to those of other nutrients, the whole supply of that nutrient will be taken up by the crop. When the supply of a particular nutrient is large compared to those of other nutrients, crop growth is limited by the low availability of the other nutrients and the crop cannot make use of the whole supply of the particular nutrient. Then the *actual uptake* is less than the *potential supply*.

The potential supply is enlarged by application of fertilizers. A part of the applied nutrient is made unavailable to crops by processes like microbial immobilization and chemical precipitation, and a part is lost by *e.g.* leaching and volatilization. The fraction that is recovered by the crop varies from zero to about 0.8. Under otherwise comparable conditions the recovery of a fertilizer nutrient by the crop is the higher, the

Table 1. Equations for calculating grain yields of maize (kg/ha) corresponding with maximum accumulation (YNA, YPA, YKA) and maximum dilution (YND, YPD, YKD) of N, P and K in the crop. UN, UP and UK stand for actual uptake of N, P and K in kg/ha

$YNA = 30 \times (UN\text{-}5)$	Eq. 1	$YND = 70 \times (UN\text{-}5)$	Eq. 2
$YPA = 200 \times (UP\text{-}0.4)$	Eq. 3	$YPD = 600 \times (UP\text{-}0.4)$	Eq. 4
$YKA = 30 \times (UK\text{-}2)$	Eq. 5	$YKD = 120 \times (UK\text{-}2)$	Eq. 6

lower the supply of that nutrient by the soil is. The *maximum recovery fraction* for a fertilizer nutrient is a function of soil, weather and crop properties.

When a nutrient is poorly available compared to the other nutrients and growth factors, it is diluted in the plant and its content goes down to a minimum value. On the contrary, when a nutrient is abundantly available, it accumulates in the plant till its content reaches a maximum value. Given a certain uptake of N, P or K, the possible yields range between the yields that correspond with *maximum accumulation* and *maximum dilution*, respectively, which are denoted by YNA, YND, YPA, YPD, YKA and YKD (Table 1).

Scheme of calculations

First the *potential supplies* of N, P and K have to be assessed. This can be done along various ways which are discussed in the next section.

The *actual uptake* of a nutrient is calculated as a function of the potential supply of that nutrient in relation to the potential supplies of the other nutrients. The curve of actual uptake against potential supply of a nutrient consists of three parts. At low values of the potential supply (situation A) actual uptake equals supply, at medium values (situation B) the curve is parabolic, and at high values (situation C) the actual uptake has reached a maximum value that is determined by the potential supply of the other nutrients (Table 2). The actual uptake of each nutrient is calculated twice, taking into account the potential supplies of the second and the third nutrient, respectively. The lower of the two values is considered the more realistic one, in conformity with the Law of the Minimum.

With the data for actual uptake the yields that correspond with *maximum accumulation* and *maximum dilution* are calculated (Table 1). To produce any grain, maize plants must have a minimum size, for which the required uptakes per ha are 5 kg N, 0.4 kg P and 2 kg K. Therefore, these values are subtracted from UN, UP and UK in the equations of Table 1.

Next the *yield ranges* found for the three nutrients are *combined* to one yield estimate. Principles for this combining are that the estimated yield lies in the overlap if yield ranges overlap, and that it can never exceed the upper limit of the lowest yield range if there is no

Table 2. Equations for the calculation of the actual uptake of Nutrient 1 as a function of the potential supplies of Nutrients 1 and 2. S1 and S2 are the potential supplies of Nutrients 1 and 2. The symbols a, d and r refer to the constants in the equations of Table 1; their values are also indicated. Situations A, B and C are explained in the text.

Situation	Condition	
A	$S1 < r1 + (S2 - r2)(a2/d1)$	
C	$S1 > r1 + (S2 - r2)(2 \times d2/a1 - a2/d1)$	
B	S1 in between	
	Equation for U1(2)	
A	$U1(2) = S1$	Eq. 7
C	$U1(2) = r1 + (S2 - r2)(d2/a1)$	Eq. 8
B	$U1(2) = S1 - \dfrac{0.25(S1 - r1 - (S2 - r2)(a2/d1))^2}{(s2 - r2)(d2/a1 - a2/d1)}$	Eq. 9

Nutrient	Values of constants		
	a	d	r
N	30	70	5
P	200	600	0.4
K	30	120	2

overlap. For the calculation of the yield within an overlap of the yield ranges of two nutrients, a parabolic equation has been derived (Janssen *et al.*, 1990). After calculation of yields for nutrient pairs, (N and P, N and K, P and K), the yields for paired nutrients are averaged. This average is the final yield estimate.

Assessment of potential nutrient supplies and maximum fertilizer recovery fractions

Various procedures can be followed to estimate the potential supplies of nutrients by the unfertilized soil and the maximum recovery fractions of applied fertilizer nutrients.

Nutrient uptake in fertilizer trials

This method is the most thorough but also the most expensive one. The experiments should be designed in such a way that each of the nutrients is in turn the most limiting growth factor. The concept is illustrated with the examples of Table 3, presenting the N uptakes and yields obtained in a fictitious factorial trial with four N, three P and three K rates. The actual uptake of N is expected to equal or closely approach the potential supply of N for the units receiving no N and high P and K applications. If no N is applied, the uptakes of N are 38, 65, and 66 kg/ha at P rates of 0, 100 and 200 kg/ha, respectively. The N uptake strongly depends on P, while an effect of K shows up only at the highest P level. In view of the very small difference in N uptake between P100 and P200, it is not likely that considerably higher N uptakes will be found at still higher rates of P and K. Hence, the potential supply of N by the soil alone can be estimated at 66 kg.

In a similar way it can be argued that the potential N supply is about 91, 115 and 160 kg/ha, when fertilizer N is applied at rates of 50, 100 and 200 kg/ha, respectively. The corresponding apparent recovery fractions of fertilizer N are 0.50, 0.49 and 0.47, respectively. They are calculated as the difference in N uptake between the units with and without fertilizer N, divided by the applied amount of N. A higher recovery fraction might be found at N rates less than 50 kg/ha, but from the available data it is concluded that 0.5 is the highest possible recovery fraction. The increase in potential N supply by fertilizer N is thus calculated as 0.5 times the quantity of fertilizer N, resulting in supplies of 116 and 166 kg/ha at N rates of 100 and 200 kg. The actual uptakes increase less than the potential supplies. If no P is applied, application of N does not increase uptake of N.

Yields in fertilizer trials

Usually the uptake of nutrients is not determined in fertilizer trials or for only a limited number of the experimental units. Then one must do with yield data. Applying the equations of Table 1 some approximate estimates of nutrient supplies can be made. The yield data of Table 3 serve to illustrate the reasoning.

It is obvious that P is extremely limiting if no P is applied. Hence, it can be assumed that all available P has been taken up and that P is maximally diluted in the crop. Thus the uptake

Table 3. Nitrogen uptake and maize yield in a factorial experiment with fertilizer rates of 0, 50, 100 and 200 N, and 0, 100 and 200 P and K. All data in kg per ha

Rate of		N uptake at N rate of				Yield at N rate of			
P	K	0	50	100	200	0	50	100	200
0	0	38	38	38	38	990	990	990	990
0	100	38	38	38	38	990	990	990	990
0	200	38	38	38	38	990	990	990	990
100	0	65	88	109	146	3354	4035	4476	4967
100	100	65	88	109	146	3666	4480	5001	5553
100	200	65	88	109	146	3843	4792	5365	5891
200	0	65	88	109	147	3743	4648	5284	5931
200	100	66	91	114	159	4043	5193	6090	7433
200	200	66	91	115	160	4158	5446	6455	7951

and the supply of P by the soil is equal to: $0.4 + 990/600 = 2.05$ kg/ha (Equation 4 in Table 1).

More difficulties are met when it is tried to derive the N supply from the yield data, because the yields of the N0 treatments do not reach a plateau. It can be concluded that the N uptake at N0 P200 K200 must be at least: $5 + 4158/70 = 64.4$ (Equation 2). The potential supply of N is certainly higher.

It is still more difficult to estimate the potential supply of K. In view of the yield increases obtained when the application of N or P is raised from 100 to 200 kg/ha, it is likely that considerable higher yields than 5931 kg (Table 3) are possible for K0 treatments, So, K is certainly not maximally diluted in the plant at N200 P200 K0. Therefore the uptake of K must be noticeably higher than $2 + 5931/120 = 51.4$ kg/ha (Equation 6) and the supply of K still higher.

As a first approximation values of 65 kg N and 60 kg K for the potential supplies of N (SN) and K (SK) are substituted in the equations of Table 2 and yields calculated. This procedure is continued with higher values for SN and SK until the calculated yields agree with the measured yields.

Chemical soil analysis

In the QUEFTS system, empirical relationships between the potential supplies of N, P and K and certain combinations of chemical soil properties are applied. The used soil (0-20 cm) properties are: pH(H_2O), organic carbon, P-Olsen and exchangeable K. Additional information can be obtained from organic N and total P (Janssen *et al.*, 1990).

Nutrient uptake from an unfertilized soil

If nutrient contents in the crop have been determined, Equations 7, 8 and 9 (Table 2) can be used in a reverse way to calculate the potential supplies from the actual uptakes of the nutrients. Details of the procedure will be published later.

Maximum recovery fraction

The maximum recovery fraction of fertilizer nutrients can only exactly be found by fertilizer experiments, including chemical analysis of crops. This was shown above for N. If no estimates of the maximum recovery fractions are available, a fraction of 0.5 is used as standard for N and K, and of 0.1 for P.

Economics

Having assessed the potential supplies of N, P and K by the unfertilized soil and the maximum recovery fractions of fertilizer N, P and K, yields can be calculated for any combination of fertilizer N, P and K. Of practical interest is to find the most economic combination. Table 4 shows the results of the calculation of the most profitable way of allocating available money to N, P or K. Prices per kg maize, N, P and K were set at 1, 4, 8 and 2 money units. Table 4 refers to the

Table 4. Calculation of the most profitable combinations of fertilizer N, P and K, marginal yield increase (MYI), and net returns on fertilizer costs (NR). Prices per kg maize, N, P and K are 1, 4, 8 and 2 units

Fertilizer costs, unit	Rates (kg/ha) of N	P	K	Yield, kg/ha	MYI, kg/ha	NR, unit
0	0	0	0	990		
100	0	12.5	0	1659	669	559
200	0	25	0	2161	502	971
300	0	37.5	0	2532	371	1242
400	0	50	0	2819	287	1429
500	9	58	0	3044	225	1554
600	18	63	12	3265	221	1675
700	27	68	24	3485	220	1795
800	36	73	36	3705	220	1915

same example as Table 3. The supplies of N, P and K by the soil were 66.5, 2.05 and 67.0 kg/ha, respectively. The above mentioned standard recovery fractions were used. Since P is the most limiting nutrient, maximum benefit is obtained by applying only P till the yield reaches a level of about 3 t/ha where the second nutrient (N) becomes equally limiting. By applying these two nutrients in a balanced ratio the yield increases a little and then also K is limiting. For still higher yields a balanced application of all three nutrients is required: per 100 units of money it is 9 kg N, 5 kg P and 12 kg K, resulting in a yield increase of 220 kg. The calculated K rate is relatively high due to the low price assumed for fertilizer K.

The data of Table 4 suggest a linear yield increase if nutrients are applied in balanced ratios. With increasing rates other growth factors like water availability or solar radiation might become limiting. Such yield limits can be introduced in the model (in the example of Table 4, it was set at 10000 kg/ha). If the calculated yields approach that limit, diminishing returns are found.

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