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Calibration of QUEFTS, a model predicting nutrient uptake and yields from chemical soil fertility indices

E.M.A. Smaling[a] and B.H. Janssen[b]

[a]*DLO The Winand Staring Centre for Integrated Land, Soil and Water Research, P.O. Box 125, 6700 AC Wageningen, The Netherlands*
[b]*Department of Soil Science and Plant Nutrition, Wageningen Agricultural University, P.O. Box 8005, 6700 EC Wageningen, The Netherlands*

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ABSTRACT

The model QUEFTS (QUantitative Evaluation of the Fertility of Tropical Soils) was calibrated using data from maize fertilizer trials in Kenya. QUEFTS describes, in four steps, relations between (i) chemical soil test values, (ii) potential NPK supply from soils and fertilizer, (iii) actual NPK uptake, and (iv) maize grain yield, acknowledging interactions between the three macronutrients. All steps were calibrated separately, and yield a modified version of QUEFTS. Major changes were the inclusion of ambient temperature and clay content in explaining potential nitrogen supply, and the replacement of the parabolic relation between potential supply and actual uptake by an exponential relation. The goodness of fit (r^2) between measured and calculated yield was improved from 0.66 in the original version to 0.78 in the modified version of QUEFTS and, when including a boundary condition for harvest index, to 0.88. A satisfactory validation was conducted with input data from fertilizer experiments in other parts of Kenya. Sensitivity analysis revealed that changing the parameters pH and organic N by 20% caused yield differences of at least 10%.

The basic thinking and theoretical concepts underlying the original version of QUEFTS still apply to the modified version. Agronomists in tropical environments are encouraged to collect the relatively few input data to further validate the two versions of the model. As a consequence, QUEFTS can contribute to a more efficient procurement and use of mineral fertilizers at both regional and farm level.

INTRODUCTION

In 1985, a network of seventy long-term fertilizer trials for rainfed, annual crops was established in Kenya. Interpretation of soil and climate maps was instrumental in deciding where to site the experiments, as the major goal was to formulate fertilizer recommendations that are specific for well-defined agro-ecological units (Smaling and Van de Weg, 1990). The trials generated a vast amount of data, and maize indeed responded differently to nitrogen, phosphorus and farmyard manure in the different agro-ecological units (Smaling et al., 1992). The results prove Sumner and Farina (1986) right in that "crops do not respond to a fertilizer application per se, but rather to the soil's response to that application".

Running such a number of fertilizer trials requires long-term commitment as regards financing, institutional infrastructure, and human resource development. As this can seldomly be afforded, cheaper alternatives must be sought. A nowadays much-valued alternative is the use of computer models that translate measurable climatic, soil and plant parameters into an output variable such as crop yield. Burrough (1989) recognizes (i) empirical models, describing a relation between a model output variable and its original determinants, without referring to underlying processes, and (ii) mechanistic process-models, describing a particular process in terms of known physical laws.

Researchers use a variety of mathematical models to empirically predict crop response to nutrients supplied in fertilizer. Cochrane (1988) described an exponential yield prediction model, whereas Waugh et al. (1975) obtained satisfactory results with a linear-plateau model. Cerrato and Blackmer (1990) discussed why one model is selected over others and found the quadratic-plus-plateau model best describing yield responses in their study. Next to fertilizer, Mombiela et al. (1981) included initial soil nutrient level in their model. The pathways of the different nutrients were, however, left unstudied.

Of a very different nature are dynamic nutrient uptake models as described by Kovar and Barber (1988) and Chen and Barber (1990). They did in-depth studies on the pathways of phosphorus, predicting its uptake by plant roots from size and morphology of the root system, kinetics of P absorption by the root and mass flow and diffusion rates. Hoffland (1991) used similar inputs to describe the effect of organic acid exudation on (rock) phosphate uptake by rape (*Brassica napus*) Caassen and Barber (1976) predicted K uptake from diffusion coefficients, initial K^+ concentration in soil solution, and buffering capacity. De Willigen (1991) evaluated fourteen dynamic models, describing turnover of nitrogen in the soil–crop system.

Sumner and Farina (1986) denounce the "spread and measure" approach followed in the empirical models. They do not contribute anything to our understanding of the processes involved in the measured yield responses, and they are valid only for soils on which the experiments were conducted. The mechanistic models are very meaningful from an academic point of view, considerably increasing our knowledge on processes in the soil–plant interface. Their main disadvantage is their complexity and associated lack of practical significance, especially for tropical countries, as they often require input data that are hard to gather on a routine basis. Moreover, rural development programmes in these countries are largely geared towards proper management of agricultural resources rather than to research per se. For such purposes, models are required that have few and easily measurable input parameters, but are still as much process-based as possible. Wolf et al. (1989) tried to find this balance in modelling crop response to soil and fertilizer nitrogen.

Next to external inputs such as mineral and organic N fertilizer, supply of N by rainfall, flood and irrigation water and biological fixation, data were needed on internal fluxes between labile and stable nutrient pools, their initial sizes, and the time constants of conversion between pools. Osmond et al. (1992) recently applied this model for soils in different parts of the tropics and obtained satisfactory results.

Most models describing relations between nutrient supply, uptake and crop yield address a single nutrient. In agricultural practice however, at least the three macronutrients should be taken into account. This principle is the major cornerstone of the model QUantitative Evaluation of the Fertility of Tropical Soils (QUEFTS), which takes N, P and K into consideration, as well as the interactions between them (Janssen et al., 1990). QUEFTS has both empirical and theoretical components, and describes relations between (i) chemical soil tests, (ii) potential NPK supply from soils and fertilizer, (iii) actual NPK uptake, and (iv) maize grain yield.

In this article, QUEFTS is run with input data from fertilizer experiments, conducted in 1990, in different agro-ecological units in Kenya. As some soils do not meet the boundary conditions of the model, the results are only partly satisfactory. Consequently, the data are employed in a major calibration exercise, so as to widen the applicability of QUEFTS. Finally, a validation is done using input and yield data from fertilizer trials in other parts of Kenya and from different years, and a sensitivity analysis then reveals to what extent changes in input parameters affect model output.

MATERIALS AND METHODS

Theoretical background of QUEFTS

QUEFTS calculates the yield of maize on tropical soils as a function of the availability of soil and fertilizer N, P and K. A value for potential grain yield must be entered (standard setting is 10,000 kg/ha at 12% moisture), but below this level, maize production must be limited by the supply of N, P and K only. In other words, water supply during the growing season, and other extraneous factors such as waterlogging, deficiencies of other nutrients or weed infestation, should not adversely affect crop development.

The calculation procedure in QUEFTS consists of four successive steps. The essential equations for each step are given in Table 1.

Step I

The potential supply of soil nitrogen, phosphorus and potassium (SN, SP, SK), i.e. the maximum quantity of those nutrients that can be taken up by maize if no other nutrients or other growth factors are limiting, is derived from empirical equations with soil chemical properties of the 0–20 cm soil

TABLE 1

Relations between soil parameters, potential nutrient supply, actual nutrient uptake and maize grain yields for the original QUEFTS (after Janssen et al., 1990)

Step I

$SN = 17 \times (pH-3) \times N_{org}$, or $1.7 \times (pH-3) \times C_{org}$

$SP = 0.014 \times (1-0.5 \times (pH-6)^2) \times \text{total P} + 0.5 \times \text{P-Olsen}$, or $0.35 \times (1-0.5 \times (pH-6)^2) \times C_{org} + 0.5 \times \text{P-Olsen}$

$SK = 250 \times (3.4 - 0.4 \times pH) \times K_{exch} / (2 + 0.9 \times C_{org})$

Step II

Situation	Condition
A	$S_1 < r_1 + (S_2 - r_2)(a_2/d_1)$
C	$S_1 > r_1 (S_2 - r_2)(2 \times d_2/a_1 - a_2/d_1)$
B	S_1 in between
	Equation for $U_{1(2)}$:
A	$U_{1(2)} = S_1$
C	$U_{1(2)} = r_1 + (S_2 - r_2)(d_2/a_1)$
B	$U_{1(2)} = S_1 - \dfrac{0.25[S_1 - r_1 - (S_2 - r_2)(a_2/d_1)]^2}{(S_2 - r_2)(d_2/a_1 - a_2/d_1)}$

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

Step III

$YNA = 30 \times (UN-5)$ $YND = 70 \times (UN-5)$

$YPA = 200 \times (UP-0.4)$ $YPD = 600 \times (UP-0.4)$

$YKA = 30 \times (UK-2)$ $YKD = 120 \times (UK-2)$

Step IV

$YE = (YNP+YNK+YPN+YPK+YKN+YKP)/6$

layer as independent determinants. Soils should be well drained and deeply rootable, with a $pH(H_2O)$ of 4.5–7.0, organic C<70 g/kg, organic N<7 g/kg, total P<2000 mg/kg, P-Olsen<30 mg/kg, and exchangeable K<30 mmol/kg.

Step II

If the supply of one nutrient is enhanced, it can positively influence the uptake of other nutrients. There are many documented examples of such interactions (e.g. Van Keulen and Van Heemst, 1982; Sumner and Farina, 1986; Kamprath, 1987). In QUEFTS, these interactions are reflected in the way actual uptake of each nutrient (UN, UP, UK) is calculated, namely as a function of the potential supply of that nutrient, taking into account the potential supply of the two other nutrients. It is a theoretical relation, assuming a linear decrease of dU/dS from 1 to 0. Integration of this differential equation results in a parabolic curve (Situation B), bounded by a linear relation between potential supply and actual uptake when the supply of the particular nutrient is low compared to the two other nutrients (Situation A), and a plateau value at a relatively high potential supply of the nutrient, implying that increased supply does not lead to any further uptake of that nutrient (Situation C).

Step III

When the potential supply of a nutrient is low compared to the two other nutrients, the particular nutrient is growth-limiting, and its internal concentration in the plant is low, eventually reaching a stage of *maximum dilution.* Nutrient use efficiency (NUE), i.e. the economic yield produced per unit of nutrient in the above-ground dry matter, is then maximum. Values of maximum NUE for maize are 70, 600 and 120 kg grain per kg N, P and K. When the supply of a nutrient is large and growth is not limited by the uptake of that nutrient, the crop takes up more than required until *maximum accumulation* is reached, coinciding with NUE values of 30, 200 and 30 kg grain per kg N, P and K. Moreover, there has to be a minimum uptake (5 kg N, 0.4 kg P, 2 kg K per ha) before any grain filling can take place. At this point, three yield (Y) ranges can be calculated, represented by maximum dilution (D) and accumulation (A) of N, P and K in the plant tissue: YND–YNA, YPD–YPA and YKD–YKA.

Step IV

The final yield estimate (YE) is found by comparing the three ranges. The yield range that follows from N uptake is narrowed to the overlap with the range YPD–YPA, leading to a combined estimate YNP, and to the overlap with the range YKD–YKA, with a combined estimate YNK. The same procedure is followed for P and K, and provides six estimates: YNP, YNK, YPN, YPK, YKN, YKP. The final yield estimate is the average value of these six combined estimates, and lies in the common overlap of the three yield ranges.

The potential supply of a nutrient is enlarged by application of fertilizers. Part of the fertilizer is made unavailable, either temporarily (immobilization, retention) or permanently (leaching, gaseous losses, erosion). The fraction recovered by the crop is a function of soil, weather and crop properties. The relation between the amount of N fertilizer applied and N uptake is often a straight line over a considerable range of applications. For phosphorus, the situation is more complex, as the reactions between P in soil solution and the solid phase are not of simple first-order kinetics. Potassium takes an intermediate position. Continuous additions change the K equilibrium between

TABLE 2

Location and soil data of fertilizer trials in Nyanza and Coast Province, Kenya

Site	District	Location	Altitude (m)	Properties of unfertilized soil (0–20 cm layer)									Soil classification (FAO, 1988)
				sand (%)	silt (%)	clay (%)	C_{org} (g/kg)	N_{org} (g/kg)	total P (mg/kg)	P-Olsen (mg/kg)	K_{exch} (mmol/kg)	pH–H_2O	
a	Kisii	Kiamokama	2020	25	32	43	27.0	2.6	530	2.3	5.5	5.2	Humic Nitisol
b	S. Nyanza	Oyugis	1450	22	22	56	21.3	1.7	760	5.3	11.3	6.4	Luvic Phaeozem
c	S. Nyanza	Rongo	1440	83	6	11	11.5	1.0	380	3.0	4.3	5.9	Humic Acrisol
d	S. Nyanza	Rodi Kopany	1330	27	14	59	25.3	1.8	1100	18.7	9.7	6.6	Eutric Vertisol
e	S. Nyanza	Homa Bay	1190	25	10	65	27.3	2.0	1650	9.7	14.2	7.9	Haplic Phaeozem
f	Kwale	Shimba Hills	130	76	14	10	6.5	0.4	70	0.5	1.6	6.0	Haplic Alisol
g	Kilifi	Chonyi	75	7	20	73	21.7	1.6	380	2.3	5.4	7.4	Dystric Vertisol
h	Kilifi	Tezo	25	88	6	6	6.3	0.6	120	1.5	2.5	7.2	Cambic Arenosol

the adsorption complex and the soil solution, thus affecting the amount available for uptake.

Similar to the concept of potential supply, QUEFTS uses the concept of maximum fertilizer recovery (Janssen and Guiking, 1990). Nitrogen recovery, for example, is calculated as the difference in N uptake between an experimental unit receiving NPK and an unit receiving PK, divided by the amount of applied N. If no field data of maximum recovery fractions are available, QUEFTS uses standard values of 0.5 for N and K, and 0.1 for P.

The literature shows little consensus with respect to methodology of measuring fertilizer recovery (FAO, 1983; Harmsen and Moraghan, 1987; Morel and Fardeau, 1990; Walters and Malzer, 1990). The difference method, used in the present study, tends to overestimate recovery because of increased root proliferation and a priming effect on N and P mineralization caused by fertilizer application. Several authors strongly advocate isotope-dilution techniques to follow the fate of the labelled nutrient. An important methodological disadvantage, however, is that substitution of a nutrient between pools (mineralization–immobilization turnover) is not accounted for and leads to underestimation of recovery. A practical disadvantage is the difficulty of applying the isotope-dilution method under field conditions.

In long-term experimentation, P recovery may be overestimated considerably as a result of a gradual build-up of residual fertilizer P, applied during previous seasons. A model was developed, calculating P accumulation and residual P recovery under such circumstances (Wolf et al., 1987). It was found that each year, 20% of labile residual fertilizer phosphorus is transferred to stable residual phosphorus (Janssen et al., 1987). The P recovery in year t (R_t) can then be calculated, at least for about 4 to 5 years (Janssen and Wolf, 1988), as a function of recovery during the first year of application (R_1), as shown in eqn. (1):

$$R_t = (0.8 - R_1)^{t-1} \times R_1 \quad (1)$$

Model calibration

The calibration of QUEFTS was based on fertilizer trials (4^2 NP randomized complete block design, four replications) in Nyanza and Coast Province. Data on soils (composite samples of the 0–20 cm layer), agro-climate and maize varieties are given in Tables 2 and 3. In order to calibrate Step I, soil analysis was required from plots that underwent treatments N_0P_0 (control plots), $N_{50}P_0$, N_0P_{22}, $N_{50}P_{22}$, $N_{75}P_{33}$. SN was derived from treatment N_0P_{22}, assuming that all soil-supplied N was taken up by the maize plant (UN = SN). Similarly, SP was derived from P uptake in treatment $N_{50}P_0$, and SK from K uptake in treatments $N_{50}P_{22}$ or $N_{75}P_{33}$. Next, grain yield and total dry matter were determined soon after physiological maturity, as well as total N, P and

TABLE 3

Crop and agroclimatic data for fertilizer trials in Nyanza and Coast Province, Kenya

Site	Maize variety	Growth duration*	Temperature (°C)**	Rainfall (mm)**
a	Hybrid 625	192	19.2	1490
b	Hybrid 622	146	20.9	1890
c	Hybrid 622	146	20.9	1675
d	Hybrid 512	145	21.8	1400
e	Hybrid 512	126	22.5	1220
f	Coast Composite	124	25.7	1300
g	Coast Composite	117	26.6	1160
h	Coast Composite	113	25.3	1060

*Major growing period 1990, period between emergence and physiological maturity.
**Mean ambient temperature during the growing period and mean annual rainfall, obtained from nearest long-term recording site.

K uptake. Data collection took place during the 1990 long rains (February–August). The experimental plots concerned had received the same treatments through the years 1987–1989. Different varieties of maize were grown at a spacing of 0.75×0.60 m (2 plants per hole after thinning). Husbandry practices at all sites included application of triple superphosphate (at planting), calcium ammonium nitrate (topdressing), and the pesticide Dipterex against African maize stalkborer *(Buseola fusca)*. More details on the trial design are provided by Smaling et al. (1992).

Values for potential grain production, required by QUEFTS as input variables were set at 12,000 (site a), 10,000 (sites b–e) and 8000 kg per ha (sites f–h). These figures were based on an on-going calibration of the crop production model WOFOST (Van Diepen et al., 1989) for the different maize hybrid varieties grown in Kenya (Roetter, in press).

To calibrate Step I, individual soil test values (organic N, total P, P-Olsen, exchangeable K) were plotted against SN, SP and SK. Correlations were poor, once again demonstrating that there is little sense in interpreting values of a sole property, if not at the same time values of other environmental properties are considered. Multiple regression analysis was then performed, as was done in QUEFTS, plotting combinations of soil and climatic properties against potential supply.

To calibrate Step II, values of potential supply and actual uptake at the trial sites were studied. QUEFTS assumes a parabolic relation between potential supply and actual uptake; in other words, dU/dS decreases linearly from 1 to 0. This proved to be an overestimation as regards N and K uptake at the present fertilizer trials. Therefore, other mathematical expressions were tested to describe the observed relation.

The calibration of Step III consisted of collating the yield/uptake relations

TABLE 4

Model input of sites i, j and k for validation, and of reference soils x and y for sensitivity analysis

Site	C_{org} (g/kg)	N_{org} (g/kg)	Total P (mg/kg)	K_{exch} (mmol/kg)	pH (H_2O)	Temp. factor*	Clay factor*	Recovery fraction N	Recovery fraction P	Maximum yield (kg/ha)
i	34	3.0	750	2.0	4.8	1.90	2.60	0.28	0.08	12 000
j	30	2.4	1000	12.0	5.9	2.10	2.40	0.44	0.22	10 000
k	28	1.5	440	10.0	6.0	2.30	2.60	0.38	0.12	7 000
x	20	1.5	350	5.0	6.7	3.00	2.75	0.00	0.00	10 000
y	10	0.8	100	1.5	6.7	2.50	2.75	0.00	0.00	10 000

*See Table 7 for calculation of temperature and clay factors.

as used in QUEFTS with measured values, to see whether any adjustments of the ranges coinciding with maximum dilution and maximum accumulation were deemed necessary.

Calibrating Step IV implied comparison of the measured yields with the average value of the six yield estimates YNP, YNK, YPN, YPK, YKN, YKP, as derived from the measured uptakes and the yield/uptake relations of Step III.

Model validation and sensitivity analysis

The version of the model obtained after calibration (modified QUEFTS) was validated with 1988 data from sites b and d, and with 1990 data from sites i, j and k, located in the Embu District, east of Mount Kenya. Table 4 shows the input data, used to run the model.

For sensitivity testing, two reference soils were defined: x and y (Table 4). All individual parameter and coefficients, employed in the different steps of QUEFTS, were varied by 20%, in order to test their individual impact on model output.

RESULTS AND DISCUSSION

Maize yields and nutrient uptake

Table 5 shows, for each treatment mean, maize grain yield (12% moisture), harvest index, above-ground NPK uptake, and 1000-grain weight of treatments N_0P_0 and $N_{75}P_{33}$. Grain yields and response to N and P differed largely between sites. Maize at a, for example, responded mainly to P and hardly to N, whereas the reverse was true for e. At g, there was hardly any response at all, whereas at h, maize only responded to the application of both

TABLE 5

Grain yield (at 12% moisture), harvest index, total above-ground nutrient uptake, and 1000-grain weight at different fertilizer rates; each figure is average value of four replications

Site	Treatment		Grain yield (kg/ha)	Harvest index	Nutrient uptake (kg/ha)			1000-grain weight (g)
					N	P	K	
a	N_0	P_0	2108	0.41	41.8	4.7	29.8	350
	N_{50}	P_0	2290	0.42	49.5	5.6	35.5	
	N_0	P_{22}	4862	0.48	79.2	12.3	58.4	
	N_{50}	P_{22}	5251	0.52	79.4	10.8	58.0	
	N_{75}	P_{33}	5726	0.51	No data			408
b	N_0	P_0	1308	0.26	28.7	13.2	55.4	241
	N_{50}	P_0	2589	0.33	41.7	14.6	91.2	
	N_0	P_{22}	1128	0.23	27.6	11.2	65.3	
	N_{50}	P_{22}	3143	0.35	53.1	19.2	110.2	
	N_{75}	P_{33}	3693	0.33	59.2	15.0	131.1	302
c	N_0	P_0	1892	0.29	40.3	12.0	54.3	281
	N_{50}	P_0	3057	0.37	66.8	13.6	64.7	
	N_0	P_{22}	2657	0.33	55.3	14.4	56.0	
	N_{50}	P_{22}	3879	0.37	81.6	19.4	85.5	
	N_{75}	P_{33}	4676	0.45	No data			316
d	N_0	P_0	1235	0.33	18.2	8.8	26.2	231
	N_{50}	P_0	2182	0.33	38.0	13.1	42.4	
	N_0	P_{22}	934	0.27	15.3	6.8	24.0	
	N_{50}	P_{22}	2176	0.36	27.2	10.6	42.2	
	N_{75}	P_{33}	3142	0.37	51.7	15.5	49.5	215
e	N_0	P_0	4569	0.42	62.8	23.7	94.6	375
	N_{50}	P_0	6299	0.42	108.5	35.0	126.3	
	N_0	P_{22}	4719	0.40	70.4	22.7	105.7	
	N_{50}	P_{22}	7187	0.45	113.8	37.9	133.1	
	N_{75}	P_{33}	7589	0.47	132.5	42.3	133.9	437
f	N_0	P_0	1187	0.36	25.5	3.1	25.7	264
	N_{50}	P_0	1672	0.45	36.2	4.1	29.8	
	N_0	P_{22}	2952	0.46	46.9	10.8	34.4	
	N_{50}	P_{22}	3029	0.43	59.1	11.7	50.6	
	N_{75}	P_{33}	3755	0.50	74.8	14.0	53.9	320
g	N_0	P_0	3965	0.34	91.8	16.2	95.8	253
	N_{50}	P_0	4174	0.35	109.7	18.9	90.1	
	N_0	P_{22}	3344	0.29	91.8	15.7	107.4	
	N_{50}	P_{22}	4482	0.36	111.2	20.5	108.9	
	N_{75}	P_{33}	3728	0.29	109.8	17.4	121.7	260
h	N_0	P_0	2553	0.45	37.6	6.8	42.4	265
	N_{50}	P_0	2243	0.44	44.9	6.6	46.8	
	N_0	P_{22}	2267	0.37	37.9	11.1	68.0	
	N_{50}	P_{22}	3731	0.45	66.1	16.1	77.4	
	N_{75}	P_{33}	4193	0.46	79.9	20.2	89.5	300

N and P. The sites with retarded crop development (b and d) had low harvest indices and a negative response to the application of P only. Maize at the two Vertisols (d and g) had the lowest 1000-grain weight, and no weight increase upon fertilizer application, as opposed to all other sites. Growth conditions during grain filling must thus have been suboptimal here. Table 5 further shows that fertilizer application had a positive influence on harvest index. Maize in treatments that included both N and P had higher harvest indices than the control plots in the highland varieties (a–e), but this was less convincing at the coast (f–h). Table 5 also shows various interactions between nutrients as a result of fertilizer application. Treatment N_0P_{22}, for example, had considerably higher N uptake than N_0P_0 at a and f. Similarly, treatment $N_{50}P_0$ increased P uptake, compared to uptake with treatment N_0P_0 at d and e. K uptake was enhanced by application of nitrogen (b, d), phosphorus (a), or both (c, e, f, g, h).

Fertilizer recovery

Table 6 shows that the apparent N recovery fractions ranged between 0.00 for a, and 0.87 for e. The extremely high value at e could be explained by increased root proliferation, which was observed (but not quantified) in plots of maize that received N fertilizer. Phosphorus recovery fractions ranged between 0.00 for d and 0.43 for h, and were negatively related to clay content ($r^2=0.64$) and to SP ($r^2=0.29$). The negative effect of clay can be ascribed to P fixing properties of fine soil particles. The negative effect of SP is due to the fact that the crop's demand for fertilizer P decreases with increasing P supply from the soil. Because clay content and SP were also correlated

TABLE 6

Measured potential supply, maximum apparent fertilizer recovery fraction, and build-up of phosphorus between 1987 and 1990

Site	Potential supply (kg/ha)			Recovery fraction		Total P (mg/kg)*	
	SN	SP	SK	N	P	P_0	P_{22}
a	95.7	7.5	76.3	0.00	0.24	528	560
b	31.0	18.2	174.7	0.54	0.21	734	790
c	77.2	16.3	96.1	0.53	0.26	358	372
d	21.8	19.9	65.2	0.24	0.00	1072	1152
e	100.1	41.1	146.4	0.87	0.13	1645	1669
f	50.9	4.7	80.4	0.24	0.35	74	90
g	110.0	21.8	137.6	0.39	0.07	358	385
h	43.9	8.8	96.1	0.56	0.43	112	118

*Average P content of plots that received 0 and 22 kg P per ha, respectively; sites a–e received 154 kg P per ha, sites f–h received 88 kg P per ha.

($r^2=0.45$), it was impossible to unravel their individual effects on P recovery. High P recovery values at some trials are explained by a build-up of residual phosphorus in soils, as shown in Table 6. Measured P recovery thus consisted of the first-year recovery of the application in 1990 and the residual recoveries of the applications in 1989, 1988 and 1987. Using eqn. (1), the total recovery (R) in 1990 can be calculated as:

$$R_{90}=[(0.8-R_{87})^3+(0.8-R_{87})^2+(0.8-R_{87})^1+(0.8-R_{87})^0]\times R_{87}$$

A high recovery of 0.43 (site h) should thus be interpreted as the sum of 0.04+0.07+0.12+0.20; hence, the recovery of the 1990 application is only 0.20, which is a plausible value for a sandy soil.

Model calibration

Monitoring growth conditions at the sites during the 1990 season revealed that maize at site b was partly parasitized by witchweed (*Striga hermonthica*), and at site d, a Vertisol on flat land, excessive downpour in March and April (860 mm) had caused spells of poor aeration. These extraneous influences adversely affected crop development, reflected in a low ratio between nitrogen uptake and organic soil nitrogen, and also in low harvest indices (Table 5). The two sites were thus left out of the calibration exercise; hence, only data from the remaining six sites were used for that purpose.

Step I

Soil test values of sites a, c, e, f, g and h were entered into QUEFTS. Figure 1a–c shows that the correlation between measured and calculated potential supply was poor for all three nutrients ($r^2<0.5$). One reason is that the original data set used to develop QUEFTS comprised few high-pH soils; hence, the previous testing of QUEFTS on such soils was rather weak. Of the present data set, however, three soils had a pH > 7, thus exceeding the boundary condition. A second reason for the poor correlation is that some of the soils at the trial sites did not meet boundary conditions of free drainage (g) and P-Olsen (individual plots). A third reason is that in the present calibration of Step I, N and P fertilizer applications were modest and K was not applied at all. Hence, potential supply may in some cases still exceed the measured values listed in Table 6.

The calibrated equations for the potential supply of N, P and K, following from multiple regression analysis are shown in Table 7. Correlation between measured and calculated potential supply was much improved, particularly with respect to P and K (Fig. 1d–f). Potential nitrogen supply (SN) was primarily determined by the organic N content of the soil, as in the original version of QUEFTS. Next, the data set showed that at the coastal sites (f–h), with temperatures around 26°C, the ratio of measured SN (Table 6) to or-

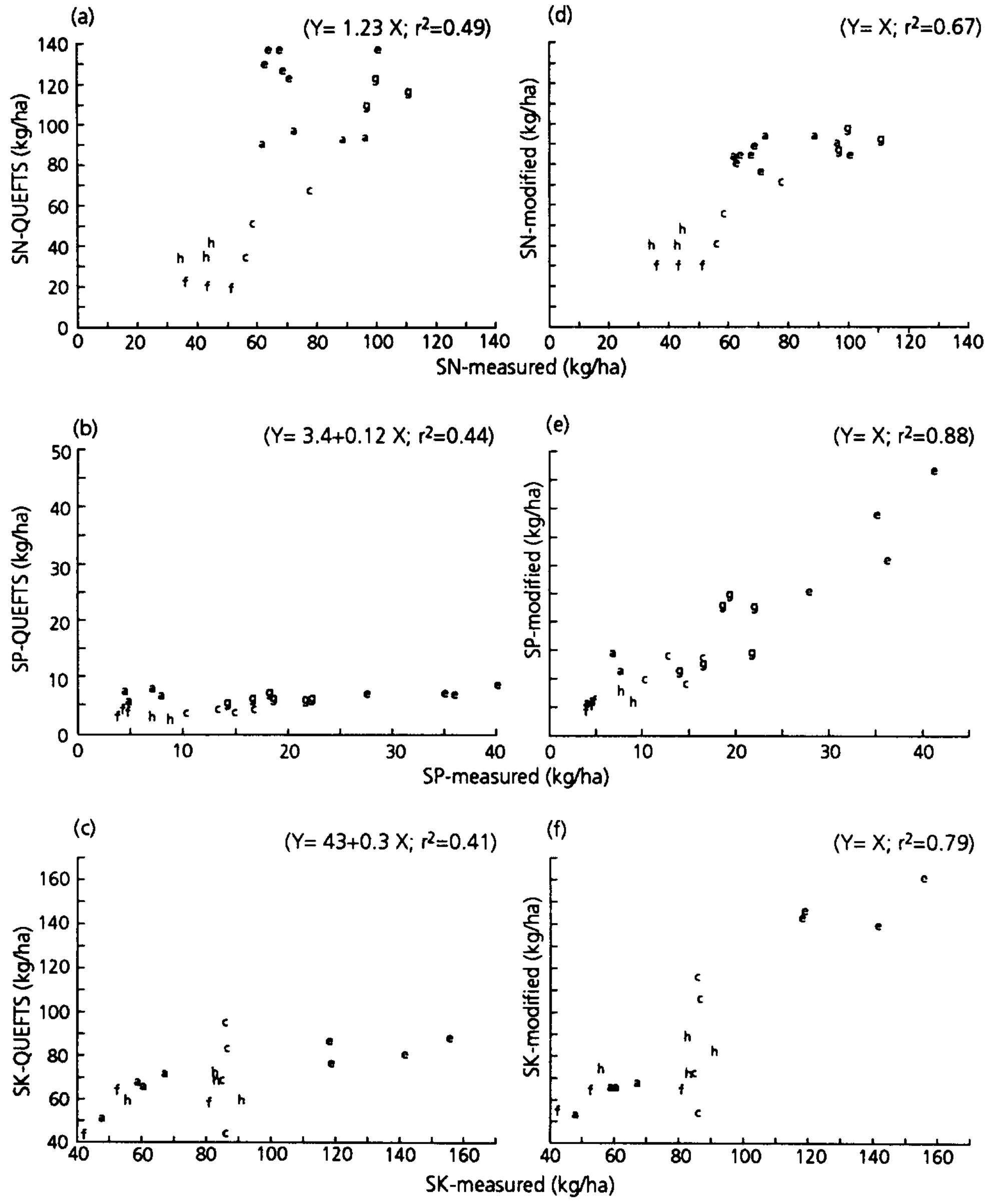

Fig. 1. Relation between measured and calculated potential NPK supply, determined by soil and climatic factors when employing regression equations of Step I (a–c: original version; d–f: modified version).

ganic soil N (Table 2) was markedly higher than at the highland sites (a–e), with temperatures around 21 °C. In the original version, this difference was accounted for indirectly by pH, which ranged between 4.7 and 6.2 in the high-

TABLE 7

Relations between soil and climatic parameters, potential nutrient supply, actual nutrient uptake and maize grain yields for the modified QUEFTS

Step I

$SN=45\times N_{org}\times\{2^{(T-9)/9}/\log(15\times clay\%)\}$

$SP=(0.0375\times total\ P+0.45\times C_{org})\times(1-0.25\times(pH-6.7)^2)$

$SK=0.35\times(2+K_{exch})\times(55-C_{org})$

Step II

Situation A: non-existent

Situation B:

$U_1=S_1\times\exp[0.5\times(c_1\times S_1/S_2+c_2\times S_1/S_3)]$

N	P	K	c_1	c_2
1	2	3	−0.05	−0.35
2	1	3	−1.15	−0.40
2	3	1	−0.35	−0.07

Situation C: $U_1=U_{1\ max}$

The curve has a maximum uptake $U_{1\ max}$, when $S_1=|0.5(c_1/S_2+c_2/S_3)|$. At this point, it is assumed that the exponential curve changes into a plateau, i.e. increased supply of nutrient (1) does not affect its actual uptake. Hence, if $S_1>|0.5\times(c_1/S_2+c_2/S_3|$, $U_1=U_{1\ max}$.

Step III

YNA =	30×(UN−5)	YND =	80×(UN−5)
YPA =	160×(UP−0.4)	YPD =	600×(UP−0.4)
YKA =	30×(UK−2)	YKD =	120×(UK−2)

Step IV

$YE=(YNP+YNK+YPN+YPK+YKN+YKP)/6$

Boundary condition: harvest index is approximately 0.4; if harvest index >0.45, YE must be multiplied by 0.5/0.4.

lands, and between 5.8 and 7.0 in the lowlands (Janssen and Van der Eijk, 1990). In the present calibration, temperature was used instead, as it proved to give a better correlation with SN than pH. The parameters employed in Table 7 reflect research on the correlation between temperature and mineralization of organic nitrogen by Jenkinson and Ayanaba (1977) and Ladd and Amato (1985). They found that mineralization rate was doubled at an increase in temperature of 9°C. Lastly, the ratio between SN and organic soil N was higher for coarse-textured soils (c, f, h) as compared to the fine-textured ones. This is in agreement with the fact that the latter soils provide a better protection against microbial decomposition (Sörensen, 1975; Lynch, 1983). Therefore, clay percentage was also included as a variable explaining SN.

Janssen and Van der Eijk (1990) interpreted the original equation for SP in Table 1 as follows. P is supplied to the crop by a labile pool, related to P-

Olsen, and by a stable pool related to $f\times$total P, in which $f=[1-0.5\times(\text{pH}-6.0)^2]$. The remainder of soil phosphorus was considered inert. At pH 6.0, $f=1$, and all phosphorus is in either the labile pool or the stable pool. The new equation in Table 7 differs from the original one in three ways. Firstly, P-Olsen is left out as it did not contribute to explaining SP. Apparently, the influence of labile P was satisfactorily dealt with in the other terms of the equation. The second difference between the original and the modified equations is that the parabolic pH curve is flatter (parameter value of 0.25 instead of 0.5), with an optimum pH of 6.7 instead of 6.0. This seems plausible, as phosphates still have a high solubility at this pH (Novozamsky and Beek, 1976). At pH 6.7, the expression $[1-0.25\times(\text{pH}-6.7)^2]$ in Table 7 equals 1.0, and SP reaches a maximum value. The third difference is that the new equation includes both total P and organic C, whereas in the original version they were used as alternatives. The new version more explicitly takes contributions from both organic and inorganic P to potential P supply into account.

Potential potassium supply (SK) was explained by the amount of exchangeable potassium and organic carbon content. Equilibrium between K^+ in soil solution and in the adsorbed fraction is controlled to a large extent by the degree of K selectivity of the adsorption complex. At increasing organic carbon content, cation exchange capacity (CEC) is also increased but, at a given exchangeable K, the relative K saturation at the adsorption complex decreases, rendering potassium less available to plants (Van Diest, 1978; Mengel and Kirkby, 1980). Larger values of CEC are also brought about by an increase in clay content. Because organic carbon and clay contents are usually positively correlated, only organic carbon was included in the equation for SK. The approach follows the now commonly accepted view that not just exchangeable K, but rather the K buffering capacity of soils is a sound measure of the K availability in soils (Uribe and Cox, 1988). On sandy soils, small applications of K increase the K^+ concentration in the soil solution appreciably and may thus result in substantial yield increases, but on fine-textured soils, K fertilizer applications hardly affect K^+ concentration in the soil solution. In the original version of QUEFTS (Table 1), the influence of organic carbon on SK was also taken into account, but the mathematical expression was different. Contrary to the original version, pH no longer contributes to explaining SK in the modified version of QUEFTS (Table 7).

Step II

Figure 2a–c gives reflections of the way QUEFTS calculates actual N, P and K uptake from the potential supply measured at the sites. Calculated and measured uptake were well-correlated for P, but the model overestimated N and K uptake, particularly at low values. Figure 2d–f shows the relations after calibration. Instead of the linear–parabolic-plateau model used in the original

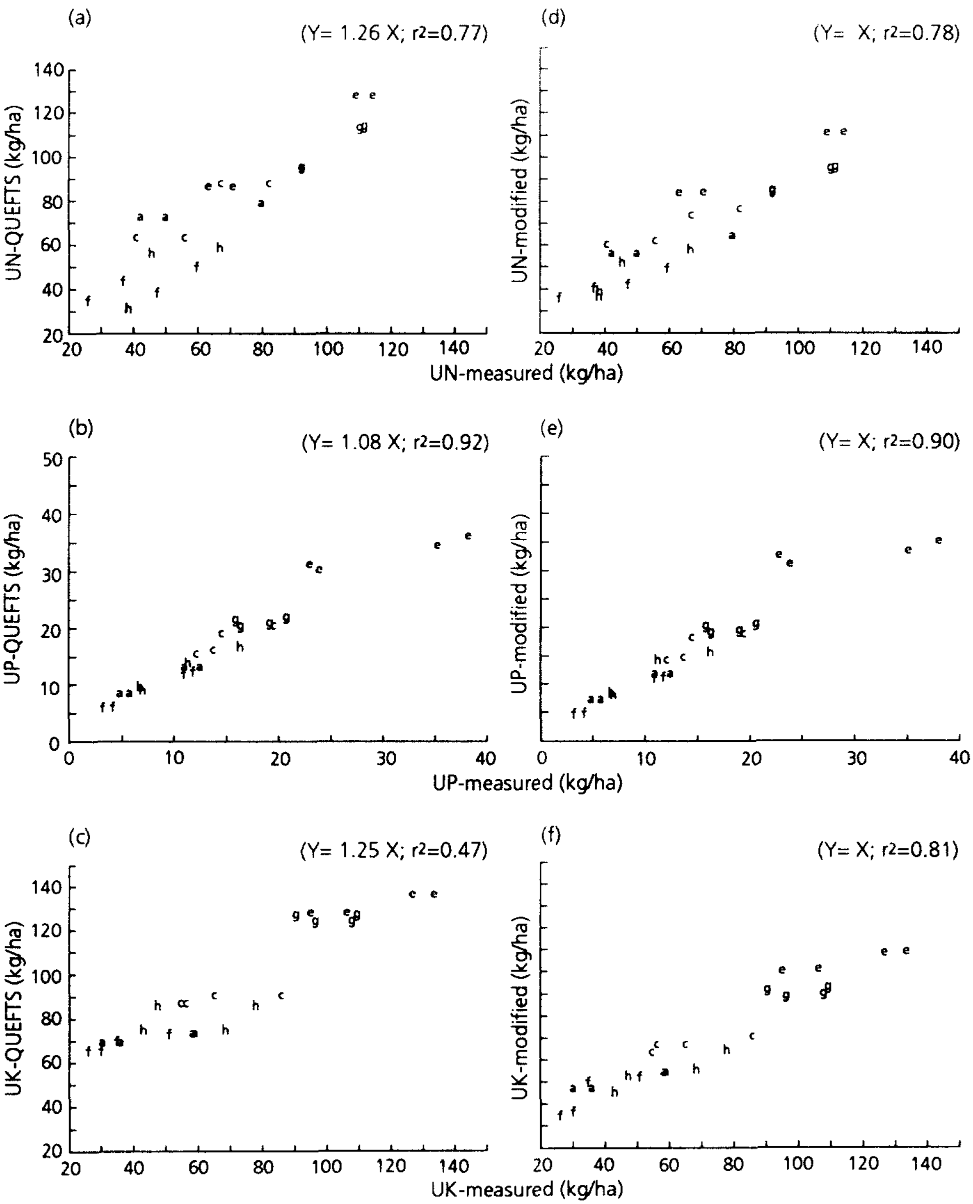

Fig. 2. Relation between measured and calculated actual NPK uptake, as determined by measured potential supply when using Step II equations (a–c: original version; d–f: modified version).

version (Situation A, B and C in Table 1), an exponential model better reflected the observations at the trials. Ln(UN/SN) was plotted against SN/SP and SN/SK, ln(UP/SP) against SP/SN and SP/SK, and ln(UK/SK)

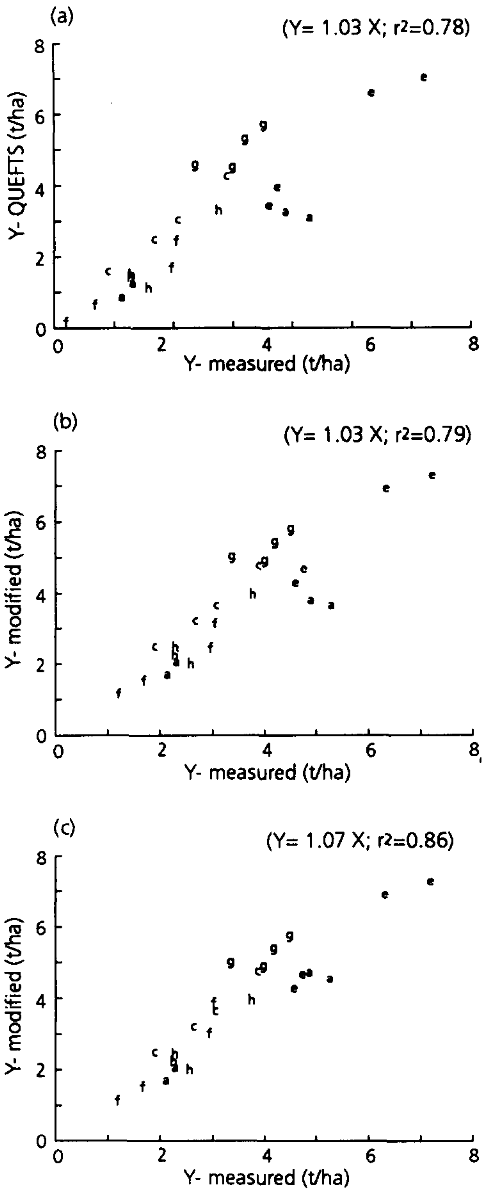

Fig. 3. Relation between measured and calculated maize yield, as determined by measured actual uptake when using yield/uptake ratios of Step III and combination of yield ranges of Step IV [a: original version; b and c: modified version, without (b) and with (c) harvest index correction factor].

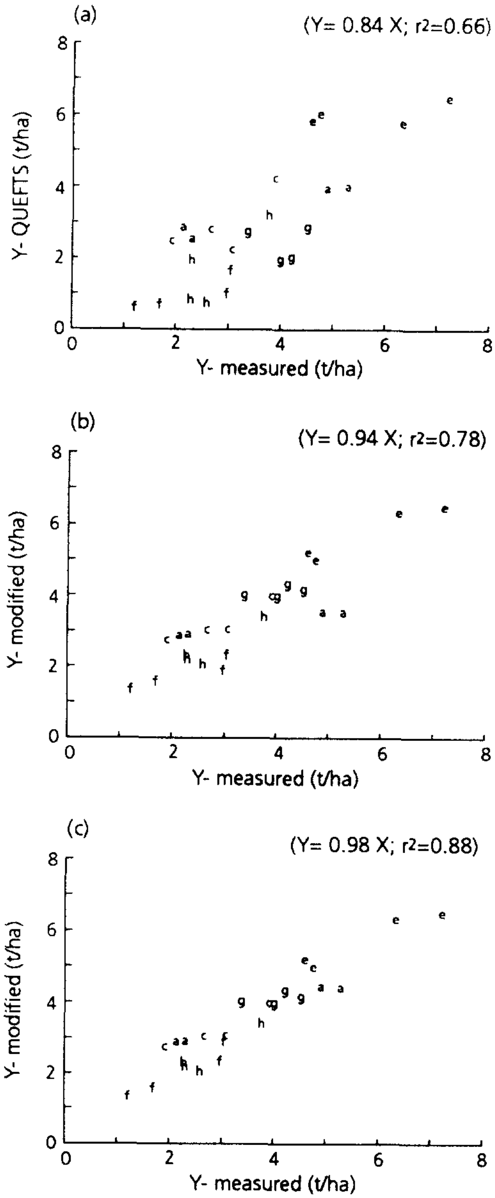

Fig. 4. Relation between measured and calculated maize yield when entering input data and running QUEFTS through the four Steps [a: original version; b and c: modified version, without (b) and with (c) harvest index correction factor].

against SK/SN and SK/SP. Each pair of regression functions was averaged, yielding new descriptions for UN, UP and UK. Rewriting the new equations gave an exponential-plateau model, still explaining uptake of each nutrient as a function of the supplies of all three (Table 7). At low supplies, the uptake of an element approaches this supply asymptotically, unlike the original version of QUEFTS, where the two have the same value until the nutrient is not maximally diluted any more (Situation A). Once the maximum uptake has been realized, it is not affected by further supply of the nutrient, and the exponential relation turns into a plateau (Situation C).

Steps III and IV

Calibration of Steps III and IV, using actual uptake as input values, gave approximately the same correlation for QUEFTS (Fig. 3a; $r^2=0.78$) and the modified version (Fig. 3b; $r^2=0.79$). Most yield/uptake ratios were well within the ranges corresponding to maximum dilution and maximum accumulation. For a number of plots, N dilution and P accumulation required a widening of YND from 70 (UN-5) to 80 (UN-5), and of YPA from 200 (UP-0.4) to 160 (UP-0.4) (Table 7).

Figure 3b shows two marked outliers, in which measured yield exceeds calculated yield, i.e. treatments including phosphorus at site a. Table 5 shows that the maize crop realized here had high harvest indices of approximately 0.5. Boxman and Janssen (1990), who conducted numerous fertilizer trials in Suriname, found that a harvest index of 0.4 can be regarded as a "normal" value for a properly managed maize crop. They also found a relation between harvest index and nutrient use efficiency. Based on these findings, maize plants with a harvest index of approximately 0.5 were multiplied by 1.25, i.e. 0.5/0.4, causing r^2 to increase to 0.86 (Fig. 3c). Lower harvest indices than 0.4 also occurred, but as this may be due to extraneous influences that were not observed, no correction was deemed justified.

Entering the input data for Step I into the original version of QUEFTS and running the model all the way without considering the different steps separately, gave a moderate correlation between measured and calculated yield ($r^2=0.66$; Fig. 4a). When applying the modified version the same way, correlation coincided with r^2 of 0.78 (Fig. 4b). When taking account of the correction factor for high harvest indices, as introduced in Step IV, r^2 is even 0.88 (Fig. 4c).

Model validation

Figure 5 shows a good correlation between measured and calculated yields for fields b and j. The calculated yields for fields d, i and k, however, were too high which can be ascribed to several unfavourable circumstances. Maize at site i was adversely affected by a very low pH, and at site k by dry spells during

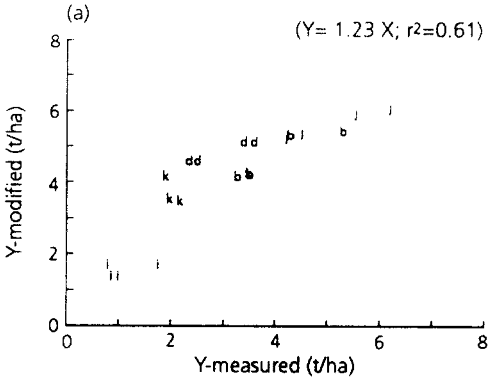

Fig. 5. Validation of the modified version of QUEFTS using data from 5 fertilizer experiments in Kenya (input data in Tables 1 and 4).

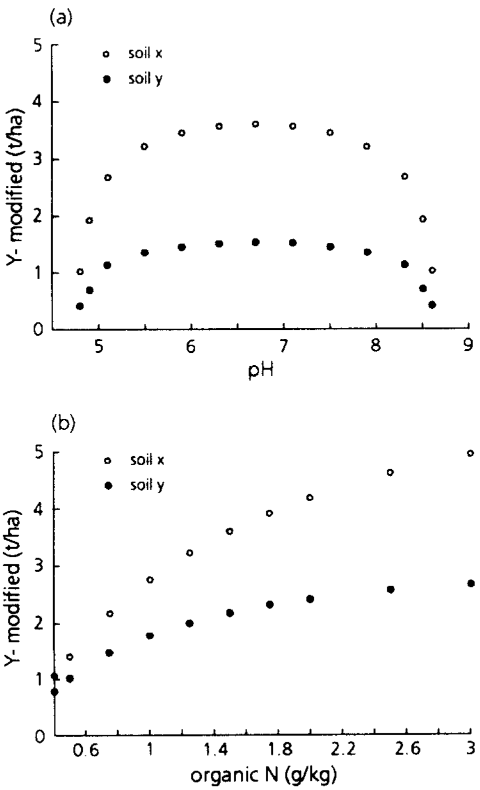

Fig. 6. Sensitivity analysis: effect of changing pH (a) and organic N (b) on maize yield calculated by the modified version of QUEFTS.

the growing season. Maize yields at site d (1988) fell short of the calculated values, indicating that the QUEFTS boundary condition that soils should at least be moderately well drained is to be maintained.

Sensitivity analysis

On employing the modified QUEFTS, calculated yields for the reference soils of Table 4 were 3616 kg per ha (soil x) and 1544 kg per ha (soil y). The most sensitive parameters causing maize yield to differ by at least 10% from the reference value were organic N, pH and temperature. All other parameter and coefficient changes caused yield changes of less than 5%. Figure 6a,b shows, how maize yields at the two reference sites varied when changing pH and organic N. Figure 6a shows that as long as pH is in between 5.5 and 7.9, effects on yield were modest; however, when pH approaches its outer limits, i.e. 4.7 and 8.7, the modified version gave considerable yield declines, even when pH was varied by a mere 0.1. In the present data set, sites a and i approach the lower pH limits. Figure 6b shows that organic N had a considerable impact on maize yield, and that this impact is greatest at low values of organic N. This applies to site f and h of the present data set.

CONCLUSIONS

(1) This article shows a calibration of the QUEFTS model, based on data collected from fertilizer trials in Kenya. The calibration involved some major parameter changes (Step I and II), but minor changes in the values of coefficients (Step III and IV). Although new relations were found, the basic structure and theoretical concepts of QUEFTS stood firm. With the modified version, the goodness of fit (r^2) between measured and calculated yield was improved from 0.66 to 0.78. When employing a correction factor for maize with a high harvest index, r^2 was even improved to 0.88.

(2) In analyzing the different steps in QUEFTS, the largely empirical Step I gave a relatively low correlation (Fig. 1a–c). Upon calibration, new relations were established which gave a much higher correlation (Fig. 1d–f). Boundary conditions in the modified version are that $4.7 < \text{pH} < 8.0$, and soils should at least be moderately well drained.

(3) Parameters employed to calculate SN had a relatively high sensitivity with respect to model output. As calibration of Step I for N did not give a very high goodness of fit either (Fig. 1d; $r^2 = 0.67$), there is a need to further study this relation, and possibly include components of a model by Wolf et al. (1989), who included mechanistic components in their model on crop response to the supply of nitrogen.

(4) In Step II, the assumption that the decrease of the N and K uptake/supply ratio was linear at increasing supply rates appeared to be an overesti-

mation, causing relatively low correlation (Fig. 2a–c). It was replaced by an exponential model, which adequately describes a more rapid decrease of N and K uptake at increasing supply (Fig. 2d–f). Moreover, in the modified version, the uptake of an element is always lower than the supply, unlike the original version of QUEFTS, where the two have the same value until a certain threshold is surpassed.

(5) Steps III and IV did not need major calibration as such, but were extended with an extra boundary condition for high harvest indices, which appeared to affect yield/uptake relations. Normal crop development is assumed to bring about harvest indices of approximately 0.4.

(6) The development of a modified version does not imply that the original version of QUEFTS has become obsolete. Both versions require thorough validation in different tropical environments. Agronomists in the tropics should be encouraged to collect the relatively few data that are needed to run both versions of QUEFTS; only then can the model become a management tool to assist agronomic and policy decisions in land use planning and fertilizer use at farm and regional level. Increased efficiency of fertilizer use has many beneficiaries, including the farmer, the national economy and the environment.

(7) Interpretation of soil test values and, to a lesser extent, plant analysis is hampered by the often high inherent spatial variability of soil properties, which is not entirely random (Trangmar et al., 1985), and inter- and between-laboratory variability in the quality of analysis (Pleysier, 1989). As QUEFTS to a large extent uses soil test values as model input, sampling and analytical quality is of utmost importance for a successful model run. In addition, a lot more understanding of the relations between nutrient supply and uptake and crop yield is gathered when plant analysis would be carried out on routine basis in fertilizer trials.

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