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REGULAR ARTICLE

Simple models and concepts as tools for the study of sustained soil productivity in long-term experiments. II. Crop nutrient equivalents, balanced supplies of available nutrients, and NPK triangles

Bert H. Janssen

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Abstract Two NPK factorial trials, one in Vietnam and one in The Netherlands were (re-)analyzed to find causes of success or failure with regard to sustained soil productivity, using the concept of crop nutrient equivalents (CNE). A (k)CNE is the quantity of a nutrient that, under conditions of balanced nutrition, has the same effect on yield as 1 (k)g of nitrogen. The percentages the nutrients take in the (k)CNE sum of N, P and K are plotted along the sides of a triangle. Soil, crop and input NPK are indicated in the triangle. Balanced crop NPK is found in the centre of the triangle, and required NPK inputs are on a straight line in the extension of the line trough the point of soil NPK and the centre. Experimental inputs were compared with inputs required for balanced NPK. In Vietnam, responses to P and soil available N:P:K pointed to severe shortage of P. Rice yields increased over time in dry but not in wet seasons. The lower yields in wet seasons were ascribed to insufficiently long periods between the dry and the next wet seasons for replenishment of labile soil P. In the Netherlands, four crops were grown in rotation on a former sea bottom. Only N had a strong effect on yield. Soil available N:P:K revealed low N, very high K and medium P. Recovery of fertilizer N was high because of capillary rise of groundwater and absence of leaching. In both trials, first-season chemical crop analysis would directly have detected disproportions of soil available N, P and K. This knowledge could have improved the experimental designs, optimized nutrient use efficiency and minimized losses of N and K to the environment.

Keywords Agronomic nutrient use efficiency · Factorial experiments · Flevopolder · Mekong delta · Physiological nutrient use efficiency · Residual P recovery

Abbreviations

A	Amount of a nutrient in available form
CF	Conversion factor for the translation of kCNE into kg
CNE	Crop nutrient equivalent
F	Flevoland (stands at the front of an acronym)
ISF	Ideal soil fertility
IA	Input of available nutrients
IU	Nutrient uptake from input
M	Mekong (stands at the front of an acronym)
PhE	Physiological nutrient use efficiency
PhEmax	Maximum physiological nutrient use efficiency
PhEmed	Medium physiological nutrient use efficiency

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B. H. Janssen (✉)
Plant Production Systems,
Wageningen University & Research Centre,
Wageningen, The Netherlands
e-mail: Bert.Janssen@wur.nl

PhEmin	Minimum physiological nutrient use efficiency
QUEFTS	Quantitative Evaluation of the Fertility of Tropical Soils
REC	Recovery fraction of input nutrients
REC_t	Residual recovery fraction in year (season) t
REC_{nt}	Total recovery in year (season) t after n equally large applications
SA	Soil available nutrients
SOC	Soil organic carbon
SON	Soil organic nitrogen
SU	Nutrient uptake from soil
TA	Amount of available nutrients from soil and input required for target yield
TIA	Amount of available nutrients from input required for target yield
TU	Uptake of a nutrient required for target yield
TY	Target yield
U	Uptake of a nutrient
WI	Whole input of a nutrient in available and non-available form

Introduction

It was explained in the accompanying paper that the topic of sustainability is restricted to sustained soil productivity, so to the function of soil to promote plant growth and specifically to the provision of plant available mineral nutrients. Soil productivity is considered a basic necessity, but environmental, economic and social conditions finally determine whether agricultural practices will be sustainable.

Numerous studies deal with the role of soil organic matter in sustaining soil productivity (Weil and Magdoff 2004). As long as soil organic matter remains above a certain critical level to guarantee soil structural stability, a decline of SOM does not mean that sustainability is at risk (Feller and Beare 1997; Loveland and Webb 2003). The emphasis on organic matter and N, however, bears the risk that the role of nutrients other than N is overlooked. For a good understanding of the results of long-term (fertilizer) trials, data on the uptake by the crop of the nutrients is indispensable. As appeared in the accompanying paper such information often is not available, likely because the costs involved in chemical analysis of crops have been prohibitive. Another reason why other nutrients than N frequently are not considered probably is the difficulty of handling all nutrients, or at least the three macro-nutrients N, P and K, at the same time. In this paper, the proportions of N, P and K in nutrient supply and uptake will receive special attention. For that purpose some concepts are applied that were developed to deal with balanced N:P:K proportions and optimum nutrient management.

The outcomes of two long-term factorial NPK trials, carried out in different ecological settings were (re-) analyzed. The chosen trials contained treatments that did or did not lead to sustained soil productivity. The trials had been carried out in situtions where erosion, salting-up, acidification and the like did not occur.

The objective of the present study was to find and understand with the help of the introduced tools of crop nutrient equivalents and NPK triangles the causes of success of some and of failure of other NPK combinations, The discussion is narrowed down to the following questions:

- Why did some NPK combinations not result in increasing yields?
- Would it have been possible to foresee from the beginning which of the experimental treatments were to end up in unsustained soil productivity?
- How could balanced N:P:K availability have been achieved?
- What were major differences with regard to likelihood of sustained soil productivity between the two agroecosystems?

Materials and methods

Summary description of the long-term experiments

NPK factorial trial for rice monoculture in the Mekong River Delta of Viet Nam

A 2^3 NPK experiment in the Mekong delta in Vietnam (Tan et al. 1995) was reanalyzed. Before 1975 the site was uncultivated natural wetland. Dry season is from December to March, wet season from April to August. From September to November the area is naturally flooded with deposition of fresh sediments. The soil is a heavy clay soil (57% clay). At the start, pH (1:1 water) was 5.7, P-Bray-2 and P-Olsen were 4 and 2.2 mg/kg, respectively, SOC was

26 gkg^{-1}, SON 2.8 gkg^{-1}, and exchangeable K 2.3 $mmolkg^{-1}$. The trial started in the wet season of 1986, and ended with the dry season of 1993–1994. Application levels were 0 or 1, where 1 was 80 kg of N, 17.5 kg of P and 25 kg of K. Two crops of rice (dry and wet season) were grown. Irrigation water levels were maintained at around 10 cm for most of the growth period.

NPK factorial trial on a former sea bottom in the Netherlands

Between 1975 and 2002, an NPK factorial trial was carried out on soils in the former sea bottom in the Eastern Flevopolder, the Netherlands. The polder was reclaimed in 1957, and drainage on this site started in 1960. Between 1960 and 1974, 15 crops were grown, which together received 550 kgN and 180 kg P. The soil was a loam to clay loam, containing 16 gkg^{-1} SOC, 106 gkg^{-1} $CaCO_3$, and pH(KCl) was 7.3. In 1975, exchangeable K was 3.6 $mmolkg^{-1}$ and P-water 10 $mgkg^{-1}$. The long-term NPK trial started in 1975 with the aim to examine how long it would take to deplete these fertile soils. Sugar-beet, spring barley, potatoes, and winter wheat were grown in a 4-year rotation. Sometimes weather conditions forced to deviate from this scheme, and to grow maize or spring wheat. The experimental design was 2^3 NPK in 3 replicates from 1975 to 1993, and a 3 N · 2^2 PK factorial in 2 replicates between 1994 and 2002. Application levels were 0 or 1, where NPK at 1 was 150-65-41(62) $kgha^{-1}$ for sugar-beet, 57.5-25-41 for cereal crops, and 200-87-41 for potatoes. The N applications at N1 and N2 since 1995 were two and four thirds, respectively, of the N1 levels before 1994. The crops grown in the period 1994–1999 were chemically analyzed.

So far the results have been presented in internal reports only, apart from a poster at the 16th Conference of the International Soil Science Society (Janssen and Menkveld 1998).

Time trends of yields and crop responses to applied NPK

Cumulative yields instead of seasonal yields were plotted versus time. They were described by 2nd order polynomials forcing the regressions lines through the origin.

The response to applied P was analyzed using Eq. 1:

$$\begin{aligned} REC_{nt} &= REC_1 + REC_2 + REC_3 + \ldots . REC_n \\ &= REC_1 \cdot (1 - q^n)/(1 - q) \end{aligned} \quad (1)$$

where REC_1 stands for the recovery fraction of fertilizer P in Year 1, REC_t for the residual recovery fraction in Year t of an application in Year 1, REC_{nt} for the total recovery at time t of n successive equally large quantities of P, and q is the ratio $RECt/REC_{(t-1)}$ (Janssen and Wolf 1988). Details are explained in the accompanying paper.

Crop nutrient equivalents (CNE) and NPK triangles

It is inconvenient to judge whether N, P and K are supplied and taken up in balanced proportions or not, when the amounts are given in kg per ha. That problem is avoided when the quantities of nutrients are expressed in crop nutrient equivalents (CNE). A (k)CNE of a nutrient is defined as the quantity of that nutrient that, under conditions of balanced nutrition, has the same effect on yield as 1 (k)g of nitrogen (Janssen 1998). For maize, 1 kCNE of P is 0.145 kg P, and 1 kCNE of K is 0.8 kgK (see below for the calculation of the conversion factors).

The idea of crop nutrient equivalents (CNE) was derived from the model QUEFTS and the use of so-called NPK triangles is a further extension of it (Janssen et al. 1990; Janssen 1998). When the three nutrients, N, P and K, are expressed in (k)CNE, it is possible and it makes sense to calculate what percentage each nutrient takes in the sum of the three. These percentages are plotted along the sides of a triangular diagram (Fig. 1). At any point in the triangle FN + FP + FK = 100%, where F stands for the fraction, expressed in%, that the nutrient takes in the sum of FN, FP and FK. In the centre of the triangle, FN, FP and FK are each 33.3%. The triangle can be used to depict the NPK composition of soil available supply (SA), input of available nutrients (IA), whole input (WI) being the sum of avaible and not available input nutrients, uptake from input (IU), uptake from soil (SU), and uptake from both (U = SU + IU). The centre represents optimum nutrient uptake, in the case the triangle is used to show U.

Calculations with the QUEFTS model (Janssen et al. 1990) show that approximately 95.5% of the

available quantity of each nutrient (A) is taken up, so U/A=0.955 or A/U=1.047, when equal quantities of N, P and K (expressed in kCNE) are available. This implies that then the proportions of UN:UP:UK as well as the proportions of AN:AP:AK are 1:1:1. When the available quantities (from soil and input) are not balanced, the proportions of UN:UP:UK are closer to 1:1:1 than the proportions of AN:AP:AK. This is a consequence of the relatively more efficient uptake of the nutrient with limited availability than of nutrients that are abundantly available. (Janssen et al. 1990; Smaling and Janssen 1993). U/A of the nutrient in shortest supply may be 1, while U/A of the other nutrients is < 0.955, and may even be as small as 0.25.

Assessment of nutrient use efficiency, crop nutrient equivalents, and crop available nutrients in soil and input by means of factorial experiments

Nutrient use efficiency is split into uptake efficiency and physiological efficiency. Uptake efficiency of input nutrients is synonymous to recovery fraction (REC), which is the ratio of IU/I, where I stands for input, and IU for nutrients taken up from input. Physiological efficiency (PhE) relates the yield (Y) of the economic plant components (e.g. grains, tubers) to uptake by the whole crop. Uptake efficiency is also called capture efficiency, and physiological efficiency sometimes is named conversion efficiency (Chikowo et al. 2010), but more often internal utilization efficiency (Witt et al. 1999). Because the acronyms IE and CE may lead to confusion as the letters 'I' and 'C' have other meanings too in this article, the use of IE or CE is avoided.

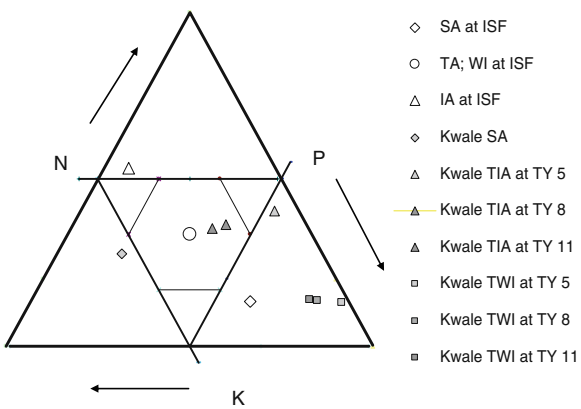

Fig. 1 NPK triangle. Along the sides, N, P and K run in the indicated direction from 0 to 100% of the sum of N, P and K (expressed in crop nutrient equivalents). At each point of the triangle, the sum of N, P and K is 100%. The thick lines within the triangle indicate a fraction of 50% of the sum of N, P and K, and the thin lines indicate a fraction of 17%. ISF stands for Ideal Soil Fertility. SA, IA and TA represent the NPK composition of the available nutrients from soil, from input and the target quantity of available nutrients (TA = SA + IA), respectively. Target inputs of available nutrients (TIA) and target whole input (TWI) for target maize yields (TY) of 5, 8 and 11 t ha^{-1} were calculated given the observed SA in Kwale (Smaling and Janssen 1993). Recovery fractions of input N, P and K were set at 0.8, 0.1 and 0.6 at ISF, and at 0.5, 0.1 and 0.5 in Kwale, respectively. WI stands for whole input. For explanation see text and appendix

PhE is highest when the nutrient is diluted in the crop, and lowest when the nutrient is accumulated. Both situations, maximum and minimum PhE, represent unbalanced plant nutrition, where one nutrient (e.g. N) is strongly growth limiting and one or both other nutrients (P and K) are at unnecessarily high levels, or vice versa. The average PhE of all three nutrients is then less than maximum possible. The medium (PhEmed) position between dilution (PhEmax) and accumulation (PhEmin) represents the balanced situation, in which the average value of PhEN, PhEP and PhEK is maximum (Janssen 1998). The ratios PhENmed: PhEPmed, and PhENmed:PhEKmed are used as multiplication factors for the conversion of kCNE (crop nutrient equivalent) of P and K into kg of P and K, respectively. For instance the conversion factor (CF) of P for spring barley is 60/200 (Table 1).

Factorial experiments offer good opportunities for the assessment of minimum and maximum PhE, maximum uptake from soil, and maximum uptake from input. The maximum uptake from the soil (SUmax) is considered to represent the available supply by the soil (SA). In the case of N, P and K, the smallest suitable design is a 2^3 factorial, in which each nutrient is found at two levels, presence or absence. Designs with more than two levels, e.g., 3^3 would even be better, but require far more extensive trials. Table 2 shows which treatments were used in the present study, unless stated differently, for the estimation of PhEmax and PhEmin, SA and RECmax. The control (N0 P0 K0) cannot be used to estimate SA because the uptake of one nutrient from an unfertilized soil may be limited by retarded growth caused by deficiency of another nutrient. In principle, the recovery of input nutrients is calculated as the

Table 1 Values of maximum, minimum and medium physiological nutrient use efficiency (PhE), and corresponding factors for the conversion of kCNE (crop nutrient equivalents) into kg, as used in this paper

PhE	Rice [a]			Spring barley[b]			Sugar-beet[b]		
	N	P	K	N	P	K	N	P	K
Maximum	96	622	115	90	300	90	135	900	90
Minimum	42	206	36	30	100	30	45	300	30
Medium	69	414	76	60	200	60	90	600	60
Conversion factor (CF)	1	0.167	0.91	1	0.3	1	1	0.15	1.5

[a] From Witt et al. 1999

[b] From not-published reports on the Flevoland trial

difference between the treatments with and without that nutrient. The difference likely is the greatest (RECmax) for the treatments at the higher level of the other nutrients, e.g., N1P1K1- N0P1K1 for RECmax of fertilizer N, as indicated in Table 2.

Nutrient inputs required for target yields

Yields estimated (YE) with the QUEFTS model are, in case of balanced nutrient uptake, approximately equal to 95.5% of the product of uptake times PhEmed. As U/A is then 0.955 (see above), YE is related to A by:

$$YE = 0.955 \cdot U \cdot PhEmed = 0.91 \cdot A \cdot PhEmed. \quad (2)$$

Equation 2 can also be used in a reverse way to calculate the amount of available nutrients (TA) required for a certain target yield (TY). In case the available soil supply (SA) is known, the target input of available nutrients (TIA) can be calculated as the difference between TA and SA. The input of available nutrients (IA) is part of the whole input (WI) of available and non-available nutrients: IA=WI · RECmax. So, the target whole input (TWI) can be calculated if the maximum fertilizer recovery fraction (RECmax) is known:

$$TA = TY/(0.91 \cdot PhEmed) \quad (3)$$

$$TIA = TA - SA \quad (4)$$

$$TWI = TIA/RECmax \quad (5)$$

The soil supplies of available nutrients, SAN, SAP and SAK, seldom are equal. To arrive at balanced nutrient supplies by soil and input, TIAN, TIAP and TIAK must be adjusted to the NPK composition of SA, as well to the level of the target yield (TY). In the NPK triangle, the optimum compositions of TIA are found on the extension of the straight line through the points of SA and the centre of the triangle (Fig. 1).

Table 2 Treatments of a 2^3 factorial preferably used for the assessment of minimum and maximum PhE, supplies of soil available nutrients (SA), and maximum recovery fractions (RECmax). For RECmax two treatments are needed, e.g., N1P1K1–N1P1K0 for the estimation of RECmaxK

Treatment code		PhE			SA	RECmax
Full	Short	N	P	K		
N0 P0 K0	Control					
N0 P0 K1	K			Min		
N0 P1 K0	P		Min			
N0 P1 K1	PK	Max			N	N
N1 P0 K0	N	Min				
N1 P0 K1	NK		Max		P	P
N1 P1 K0	NP			Max	K	K
N1 P1 K1	NPK					N, P, K

The mathematical prove for this is given in the appendix. In Fig. 1, TIA and TWI are shown for maize TY's of 5, 8 and 11 t ha^{-1}. The NPK composition of SA in Kwale, which is used as an example in Fig. 1, was (in kgha^{-1}) 50.9 : 4.7 : 80.4, as assessed in a field trial in Kenya (Smaling and Janssen 1993).

If a soil receives year after year nutrient inputs directed towards balanced amounts of available N, P and K, the NPK composition of SA will change and finally the soil becomes low in N, high in P and medium in K. This is the composition at 'ideal soil fertility' (ISF), as explained in the appendix. The points of SA at ISF and the corresponding IA (high in N, low in P and medium in K) are also shown in Fig. 1.

Results

NPK factorial trial for rice monoculture in the Mekong River Delta of Viet Nam

Yields, and responses to N, P and K

Rice yields and nutrient uptake (Tan et al. 1995) are shown in Table 3. Yields were lower in the wet than in the dry season, especially when no P was applied. In Fig. 2 cumulative yields are described by parabolic equations; the sign of the quadratic term indicates whether the yield trend was positive or negative during the experimental period. In the dry seasons (top graph), yields of all fertilizer treatments increased, but in the wet seasons (middle graph), yields decreased over time for treatments without P, and hardly changed for treatments with P. A striking difference between the dry and wet season is that in the dry season Treatment N produced somewhat higher yields than Treatment P, while in the wet seasons Treatment P gave considerably higher yields than Treatment N. Also shown in Fig. 2 (bottom) are the sums of the yields in the dry and wet seasons, i.e. the yields between two periods of natural flooding. The trial started with a wet season before the flood. Therefore the yields of the first dry and the second wet season, etc. had to be combined, resulting in seven periods. Treatments with P showed a slightly positive, and treatments without P a slightly negative time trend.

The responses to P were considerably greater in the wet than in the dry seasons and greater when N was applied than when no N was applied. In all cases the responses to P increased with time.

Nutrient use efficiency and soil available nutrients

The nutrient uptake data of Table 3 point to very low P in the crops receiving no fertilizer P. Although the number of uptake data in Table 3 is very limited, and the treatments only partly coincide with the most appropriate treatments for the estimation of PhEmax (Table 2), the maximum ratios of yield to uptake for N, P and K were calculated, using the most suitable of the available treatments (Table 4, Part A). The value for PhEPmax is the average of 1053 and 1134 kg grain per kg P taken up. These numbers are far outside the established range (Witt et al. 1999) given in Table 1. Therefore it was decided to use for the estimation of soil available P (SAP) a rounded value of 1000 kgkg^{-1} as maximum PhEP for rice. Maximum PhEN of 75 in Table 4 is between PhENmed and PhENmax in Table 1. Also PhEK of 92 in Table 4 lies between PhEKmed and PhEKmax in Table 1. It is concluded that P was extremely diluted in the rice crop in the Mekong trial, but N and K were not. The strong response to P mentioned above is in line with these findings.

In Part B of Table 4, the uptakes of N, P and K from the soil are calculated by dividing the yields by the rounded PhEmax. This was done for the treatments that would give maximum uptake of the concerning nutrient from the soil. The uptake from the soil in these treatments may then be considered as a good approximation of the available amount in the Mekong soil (MSA). The MSA data in kgha^{-1} were divided by the conversion factors for rice, presented in Table 1, to convert them into MSA data in kCNE ha^{-1}. Next, the MSA's of N, P and K were expressed in% of the kCNE sum.

In Table 4 Part C, the apparent maximum recovery fractions of fertilizer nutrients were calculated using the differences among the indicated treatments. The calculated N and K recovery fractions are low and point to losses. The REC value for P (0.3) is high and is considered to be a result of recovery from recently applied as well as from residual fertilizer P, which agrees with the increasing responses to fertilizer P discussed above. Also the original authors mention

Table 3 Mekong. Rice grain yields (averages of 8 years) in wet and in dry season, and yields and total nutrient uptake of some treatments in the last season, 1993/94 dry (Tan et al. 1995)

Treatment	Grain yield, t ha^{-1}			Uptake in 1993/94, kg ha^{-1}		
	Wet	Dry	1993/94 Dry	N	P	K
Control	2.08	3.36	3.89	53.6	4.92	58.2
N	2.23	4.07	4.99	77.2	4.74	64.9
P	3.15	3.70				
K	1.99	3.46				
NP	4.12	4.89	5.92	85.9	9.35	64.6
NK	2.24	4.01	4.99	73.9	4.4	71.2
PK	3.11	3.75				
NPK	4.27	4.97	5.92	84.8	10.31	74.1

such an effect (Tan et al. 1995). According to Eq. 1, the cumulative recovery (REC_{nt}) is 0.33 for n=16 when q is set at the standard value of 0.7 (Wolf et al. 1987). This is so close to 0.3 that it was decided to stick to the standard value of 0.1 for REC_1 in the calculations of Table 4 Part D and E.

In Part D of Table 4, the whole input of nutrients in Mekong (MWI) is expressed in kg ha^{-1}, kCNE ha^{-1}, and in percentages of the kCNE sum. Next the input of available nutrients (MIA) is calculated, and MA, the sum of MSA and MIA. The calculated NPK compositions of MSA, MWI, MIA and MA are shown in Fig. 3.

Also shown are MTIA and MTWI, which are calculated in Table 4 Part E, following the procedure of Eqs. 3, 4 and 5.

NPK factorial trial on a former sea bottom in the Netherlands

Yields and responses to N, P and K

Average dry-matter yields of the harvested crop components are shown in Table 5. It is obvious that only N had a strong effect on yield. The effect of P was more evident for sugar-beet, potatoes and maize than for wheat and barley. The calculated effect of K always had a negative sign, but was insignificant.

To follow the crop yields in the six successive rotations, rotation means were calculated. The results of treatments with and without K were averaged as the response to K was absent. The mean of the yields of a crop obtained with the treatments NP and NPK in the first rotation was set at 100%. Other yields were calculated as percentages of that yield. Next the rotation means were found as the average results of the four crops within a rotation (sugar-beet, spring barley, potatoes, wheat). The six wheat yields consisted of four winter-wheat and two spring-wheat data. The last step was the calculation of the cumulative rotation means. Parabolas through the origin gave good fits (Fig. 4). The rotation means increased over time (positive sign of quadratic terms) for the treatments with N, and decreased (negative sign of quadratic terms) for the treatments without N. Responses to P were not visible until rotation 3 or 4.

Treatment effects on nutrient uptake and soil available nutrients

In 1994 and 1998 grains and straw of spring barley, and in 1999 roots and leaves of sugar-beet were analyzed for N, P and K, and the nutrient uptake was calculated. The uptake of N, but also the uptakes of P and K, increased strongly with N application (Table 6 Part A). This indicates that considerable parts of soil available P and K were not used by the crops when no N was applied. Application of P stimulated the uptake of P. Application of K had some effect on K uptake but the application rate was small compared to the uptake of K from the soil alone. In 1998 the K uptake by barley from the soil alone was less than in 1994. This and the increasing K effect on K uptake could point to a gradual lowering of soil available K. Nevertheless, K uptake by sugar-beet in 1999 in the K0 treatments was still great.

The maximum nutrient uptake from the soil alone was calculated as a proxy of the available soil supply (FSA). The percentages of N, P and K in the CNE

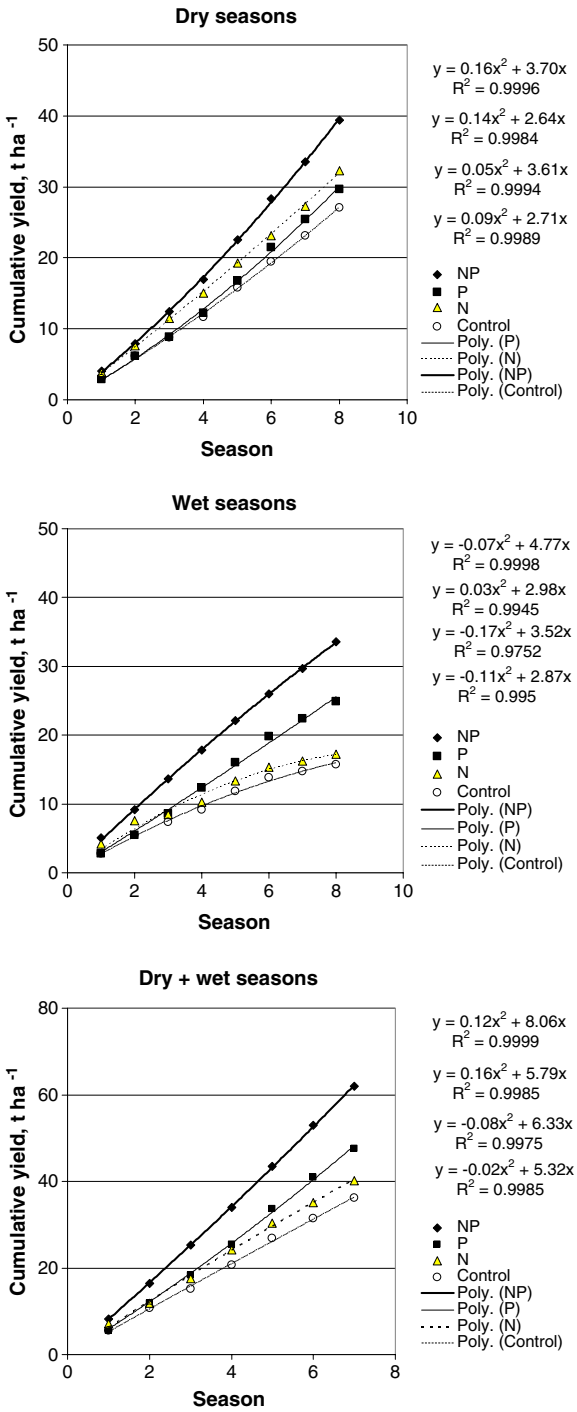

Fig. 2 Mekong. Course of cumulative rice yields in dry (*top*), wet (*middle*), and dry and wet (*bottom*) seasons together. NP, P, N and control are averages of these treatments with and without K. Regression equations are in the same order as the legend

sum of FSA point to low N, very high K and medium P in the soil (Table 6 Part B). The N, P and K uptakes by control crops (FU 0-0-0), however, are rather well balanced, except for sugar-beet where N is still low (Table 6 Part C). The crops did not take up the nutrients in proportion to their supplies.

With the data of FSA (Table 6 Part B) and fertilizer recovery fractions of 0.9 for N and K and of 0.1 for P (from unpublished reports), the NPK compositions of target inputs (FTIA and FTWI) for spring barley were calculated in a similar way as for rice in Table 4, following the procedures of Eqs. 3, 4 and 5. For P, REC was estimated at 0.3 (unpublished reports). Because this represents a cumulative recovery fraction, the standard first season recovery fraction of 0.1 was used to calculate the required P input. The points of FTIA and FTWI are shown in Fig. 5, together with the compositions of FSA and the NPK input (FIA and FWI) used for spring barley in the long-term experiment.

Discussion

NPK factorial trial for rice monoculture in the Mekong River Delta of Viet Nam

Differences between dry and wet season in Mekong

In Mekong, the limiting growth factor obviously was P, and the application of P in the experiment was too low, especially in the wet season. The better crop growth in the dry season is considered a result of more irradiation and hence higher potential yield, and of a direct after-effect of the natural flooding between the wet and dry seasons. Apparently the natural flood was adding P to the soil, as mentioned by the authors (Tan et al. 1995). The question arises why the crops did not make use of that flood P during the wet season. The cause of declining rice yields and the reversal of this decline at the International Rice Research Institute (IRRI) have been ascribed to N deficiency and improvement of N management, respectively (Dobermann et al. 2000). It is, however, difficult to understand how poor N management could be the cause of the low P availability in the wet seasons. When P was applied, the response to N was similar in the wet and the dry seasons (Table 3, NP-P; NPK-PK). Therefore the difference between the dry

Table 4 Mekong. Estimation of: A. Maximum physiological nutrient use efficiency (PhEmax). B. Soil supply of available nutrients (MSA) in Dry season 1. C. Maximum recovery fraction (RECmax) of fertilizer nutrients. D. NPK composition of whole input (MWI), input of available NPK (MIA), and of total supplies of available NPK (MA). E. Amounts of available nutrients (TA) for target yield, and corresponding input of available nutrients (TIA) and whole input (TWI)

	N	P	K
A. PhEmax			
Treatments for estimation PhEmax in Table 3	Control	N, NK	NP
Calculated PhEmax (= Y/U), kg kg^{-1}	73	1093	92
Rounded PhEmax (see text), kg kg^{-1}	75	1000	92
B. SA in Dry season 1			
Treatments for estimation MSA	P, PK	N, NK	NP
Yield[a] (Y), t ha^{-1}	2.89	3.82	4.01
Estimated MSA, kg ha^{-1} (= 1000 · Y/PhEmax)	38.5	3.8	43.6
Estimated MSA, kCNE/ha (= SA/CF[b])	38.5	23.8	47.9
Proportions,% of sum of 110.8 kCNE	35	21	44
C. RECmax			
Treatments for estimation REC in Table 3	NP-P	NP-N, NPK-NK	NPK-NP
Rounded estimated REC, kg kg^{-1}	0.35	0.30[c]; 0.1	0.4
D. Composition of MWI, MIA and MA			
MWI, kg ha^{-1} (Tan et al. 1995)	80	17.5	25
MWI, kCNE ha^{-1} (= MWI/CF[b])	80	105	28
MWI,% of 213 kCNE ha^{-1}	38	49	13
MIA, kCNE ha^{-1} (= MWI · RECmax)	28.0	10.5	11.0
MIA,% of 49.5 kCNE ha^{-1}	57	21	22
MA, kCNE ha^{-1} (= MSA +MIA)	67	33	59
MA,% of 159 kCNE ha^{-1}	42	21	37
E. Estimation of TA, TIA and TWI for a target yield (TY) of 5 t ha^{-1}			
TA, kg ha^{-1} (=TY/0.91 · PhEmed)[d],	80	13.3	73
TA, kCNE ha^{-1} (= TA/CF[b])	80	80	80
TIA, kg ha^{-1} (= TA–MSA)	41	9.5	29
TIA, kCNE ha^{-1} (= TA–MSA)	41	57	32
TIA,% of 130 kCNE ha^{-1}	32	44	25
TWI, kg ha^{-1} (= TIA/REC)	118	95	73
TWI, kCNE ha^{-1} (= TIA/REC)	118	568	80
TWI,% of 766 kCNE ha^{-1}	15	74	10

[a] Yield from Tan et al. 1995

[b] CF = conversion factor for rice. See Table 1

[c] The estimated value of 0.3 refers to a cumulative recovery after 16 applications of P. As a cumulative recovery fraction of 0.33 corresponds to a first year recovery fraction (REC) of 0.1, which is used in Parts D and E

[d] PhEmed = medium physiological efficiency. See Table 1

and the wet season likely was caused by a difference in P availability. The wet season instantly followed the dry season while the dry season started only after 3 months of natural flooding. During growth seasons the labile pool of P, and also that of K, gets more or less depleted, and in between two growing periods there must be sufficient time for the relevant chemical processes to restore these labile pools. For K, it has been shown that the length of the fallow period between two successive seasons is crucial for the replenishment of the labile pool in the Mekong delta (Hoa 2003; Hoa et al. 2006). It is hypothesized that the periods between the dry and wet seasons in the present long-term experiment were too short for replenishment of the labile P pool. Between the wet and the next dry season there was considerably more time for replenishment of the labile pool, so that treatments N and NK in the dry season could have similar yields as treatments NP and NPK, respectively, in the wet season (see Table 3, Fig. 2). For

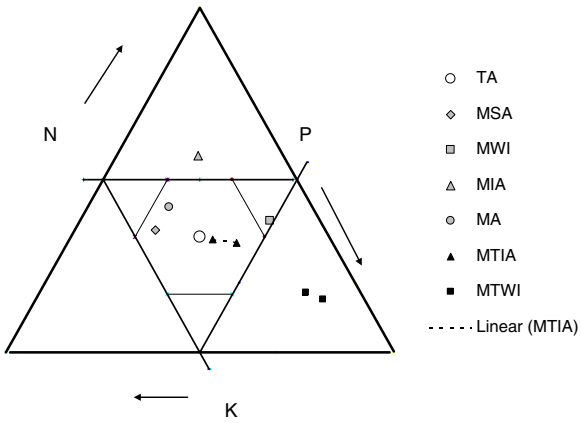

Fig. 3 Mekong. NPK compositions of soil available nutrients (MSA), whole input (MWI) and input of available nutrients (MIA), and the sum of available nutrients from input and soil (MA) in Dry season 1, as calculated from data in Tables 3 and 4. TA is the composition of the target quantity of available nutrients (TA = SA + IA). The points of MTIA and MTWI refer to target yields of 5 (*right*) and 10 (*left*) t ha^{-1}

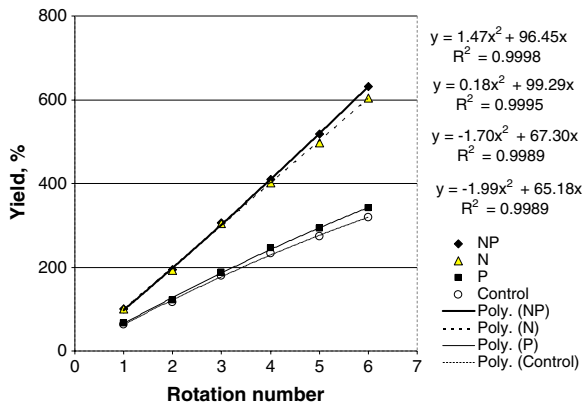

Fig. 4 Flevoland. Course of cumulative rotation yield averages. NP, P, N and control are averages of these treatments with and without K. The yield of the NP treatment in Rotation 1 was set at 100% and other yields were calculated as percentages of that yield. Regression equations are in the same order as the legend

sustainable rice production, P application at the beginning of the wet season is essential.

Need for chemical crop analysis

The continuation of the experimental treatments during 8 years has worsened the situation of severe P deficiency. Could this have been foreseen? In retrospect the answer is yes, when nutrient uptake had been assessed and the supply of soil available (MSA) had been estimated in the first experimental year. Then for any target yield, the compositions of MTIA and MTWI could have been calculated with Eqs. 4 and 5, as was done in Table 4 Part E. The points and lines for MTIA and MTWI shown in Fig. 3 illustrate once more that the applications in the long-term experiment were far too low in P.

NPK factorial trial on a former sea bottom in Flevoland, the Netherlands

N:P:K proportions

Apparently the crops did not take up the nutrients in proportion to their supplies, but selectively according to their needs (Table 6). The percentage of N in the kCNE sum was in the control crop about twice as high as in FSA, while the percentage of K in the control crop was about half as high as that in FSA. The percentage of P in the CNE sum was a little higher in the control crop than in FSA. As a consequence, the NPK composition of the control crop did not indicate that the nutrient supply by the soil was out of balance and, hence, had limited value as a diagnostic tool for recommendations on nutrient inputs.

According to calculations of FTIA there is no need at all to apply K, as long as the target grain yield of

Table 5 Flevoland. Number of harvests of six crops, average dry-matter yields of indicated crop components, and average effects on yield by application of N, P and K

Treatment	Crops and harvested crop component. All yields in t ha^{-1}					
Component	Sugar-beet Root	Spring barley Grain	Potatoes Tuber	Winter wheat Grain	Spring wheat Grain	Maize Total
Number	5	6	6	4	2	2
Average yield	11.25	4.21	10.08	5.41	5.06	8.79
N effect	6.22	2.88	4.84	3.47	3.83	3.61
P effect	1.17	0.25	0.93	−0.06	0.27	1.38
K effect	−0.53	−0.10	−0.07	−0.14	−0.20	−0.04

Table 6 Flevoland. Spring barley and sugar-beet. A. Uptake of N, P and K, averaged across all treatments, and average effects of N, P and K application on uptake (kgha^{-1}) in the years indicated. B. Maximum nutrient uptake from the soil alone (FSA), expressed in kgha^{-1}, kCNE ha^{-1}, and % of sum of kCNE. C. Uptake in the control treatment. Uptake refers to total crop (grains + straw; roots + leaves). Application rates for spring barley: 53.5 and 107 kgN ha^{-1}, 25.1 kgP ha^{-1}, 41.5 kgK ha^{-1}; for sugar-beet: 100 and 200 kgN ha^{-1}, 65.5 kgP ha^{-1}, 62.2 kgK ha^{-1}

	Spring barley 1994			Spring barley 1998			Sugar-beet 1999		
	N	P	K	N	P	K	N	P	K
	A. Average uptake and treatment effects								
Average	63	19	96	82	22	86	169	27	309
N effect[a]	58	16	100	69	15	75	154	11	217
P effect	7	6	13	−1	3	2	−2	13	−14
K effect	−3	−1	4	0	0	16	3	−1	35
Unit	B. Maximum uptake from soil alone (FSA)								
kgha^{-1}	28	24	166	40	25	108	80	28	460
kCNE ha^{-1}	28	80	166	40	83	108	80	154	307
% of sum	10	29	61	17	36	47	14	32	54
	C. Control uptake (FU 0-0-0)								
kgha^{-1}	20	7	24	34	11	31	58	16	137
kCNE ha^{-1}	20	24	24	34	37	31	58	107	91
% of sum	30	35	35	33	36	31	23	42	36

[a] Average of N1 and N2 effects

spring barley is less than 9.1 t ha^{-1}. Comparison of the point of FIA with those of FTIA in Fig. 5 shows that the applications in the long-term experiment were too low in N and P and too high in K.

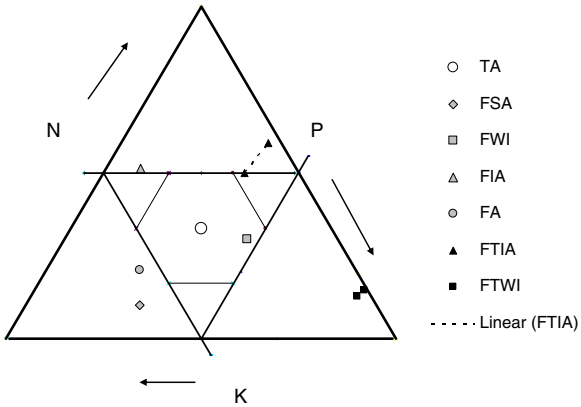

Fig. 5 NPK compositions of soil available nutrients in Flevoland (FSA), whole input (FWI) and input of available nutrients (FIA), and the sum of available nutrients from input and soil (FA) in 1994, as calculated from data in Table 6. TA is the composition of the target quantity of available nutrients (TA = SA + IA). The points and lines of FTIA and FTWI refer to target yields of 9.5 (*right*) and 12 (*left*) t ha^{-1}

Sustained soil productivity in Flevoland

The above results suggest that there is no problem in sustaining soil productivity in Flevoland, as far as it concerns NPK. The recovery fraction of fertilizer N is high because there is no leaching during crop growth and any leached nutrients may return to the rooting zone by capillary rise of groundwater in this polder. The uptake of K from the soil simply follows crop growth which in its turn is a function of N and P uptake from soil and input. Hence, there is no need to apply any K, and it may be expected that the soil supply of K is more than sufficient for some more decades. If the recommendations for FTIA and FTWI are followed, it is to be expected that SA in Flevoland gradually shifts from the present position of FSA (Fig. 5) to that of SA at ISF (Fig. 1). Once that has happened, replacement input of NPK will be sufficient for sustained soil productivity, because nutrients are hardly lost in Flevoland.

Nutrient supply from soil and fertilizer in Flevoland

The original aim of the experiment in Flevoland was to find how long it would take before inputs of N, P

and K would be needed. It was concluded that the soil supply of P was sufficient for 20 crops (Janssen and Menkveld 1998). In 2002, the last year of the experiment, there was still no need for K input, i.e. after 43 crops. It is not possible to predict on the basis of the presently available data how long the soil can continue providing sufficient K. Only prolongation of the long-term experiment could have given an answer. It is obvious, however, that the natural situation in this polder can be considered as excellent for crop production. The major reasons are that the soil originally is rich in P and very rich in K, and that there is no leaching of fertilizer N during the growing season. Further the subsoil adds to the N supply in these young polder soils. The apparent recovery of fertilizer N was close to 100% in this long-term experiment, which is not exceptional in Flevoland. It was also found in grassland (Lantinga et al. 1999). For wheat an apparent recovery of fertilizer N of 70–75% was found between application rates of 50 and 100 kgN (Spiertz and Ellen 1978); unfortunately no treatment without fertilizer N was included in their study. The capillary rise of groundwater plus dissolved nutrients contributes to the high N recovery. The capillary water also makes that crops seldom suffer from drought. In summary: these young polders allow crops to grow without stress if N and P are adequately applied. At the experimental site SOC was 16 gkg^{-1} which was considered critical in Kabete (see accompanying paper). There were no indications that 16 gkg^{-1} was too low in Flevoland, although the fraction < 20 μm was around 420 gkg^{-1} not much below 473 gkg^{-1} calculated for a soil requiring a SOC of 16 gkg^{-1}. Other reasons why soil structure is not at stake, provided not too heavy machinery is used, are that the presence of $CaCO_3$ and the high pH in Flevoland mitigate the necessity of high SOC for the maintenance of soil structure. Moreover the land is flat and not very prone to erosion.

Comparison of Mekong and Flevoland

The supplies (in kCNE) of available N, P and K of the treatment N1P1K1 were not equal, neither in Mekong nor in Flevoland. As a consequence the points of MA in Fig. 3 and of FA in Fig. 5 are not in the centre of the triangle. The fraction FP of MA was only 22% (Table 4 Part D), indicating that the nutrient supply from soil and input in this long-term trial was out of balance even for the N1P1K1 treatment in the first dry season.

In Flevoland the relative NPK composition of FA was 21-24-55 (calculation not shown), and the position of FA in Fig. 5 was in the left-hand corner of the triangle far from the centre. Fertilizer K was applied because it was an experimental treatment in the factorial design. With the knowledge obtained from the trial, however, the conclusion is that K application in agricultural practice essentially is wastage in this area.

Table 7 shows agronomic nutrient use efficiencies of fertilizer nutrients in the two agroecosystems studied in this paper. Although different crops were used, the values of AE may be compared as both are all cereal crops showing similar relations between grain production and nutrient uptake (Van Keulen and Van Heemst 1982). The low AEKs, in Mekong as well as in Flevoland, are due to high availability of K (SAK) in both soils. Flevoland has the highest AEN which is ascribed to the high recovery of fertilizer N; AEP changed from 0 initially to more than 20 in the later rotations. In Mekong, the high AEP is caused by the very high physiological P use efficiency, which in itself is a reaction to the extremely low P availability in the soil. In both locations, Mekong and Flevoland, the apparent recovery of fertilizer P was as high as 0.3, and in both cases this could be understood as the result of residual recovery of fertilizer P. It reveals the

Table 7 Comparison of the agronomic nutrient use efficiencies (kg yield increase per kg of applied fertilizer nutrient) in the two agroecosystems studied

Agronomic nutrient use efficiencies (AE)	Mekong, rice		Flevoland, spring barley
	Wet season	Dry season	
AEN	13	15	26 to 60
AEP	112	51	0 to 24
AEK	3	0	−8 to 4

increasing role of P on improving yields once the application of P has begun.

Improper NPK ratios of nutrient inputs lead to wasting of nutrients and hence to damage to the environment. This likely has contributed to losses of N and K in the Mekong study where in relation to P too much N and K were applied.

Balanced N:P:K proportions and factorial designs

Chemical crop analysis proved very helpful in understanding the crop performance in Mekong and Flevoland. The values of the soil supplies of available N, P and K (SAN, SAP, SAK) could be found thanks to the factorial designs of the trials. The interpretation of the chemical data was facilitated by conversion of mass units (kg) into crop nutrient equivalents (kCNE) and by the use of NPK triangles, thus demonstrating the value of the CNE concept. It was a pity that crops had been analyzed late and not in the beginning of the experiments. The design of the trial in Mekong could have been more efficient if already in the first season crops would have been analyzed for N, P and K, by preference in both the dry and wet season and in all experimental treatments. The low P availability, especially in the wet season, would have shown up clearly in the percentage SAP takes in the sum of SAN, SAP, and SAK, and the design of the experiment could have been redressed on time. P uptake in control treatment does not give that information. In the Flevoland experiment, the excessive amounts of soil available K did not show up in the analysis of the crop of the control treatment. Because of the selective nutrient uptake by crops, the proportions of NPK in the crop are considerably different than the proportions of NPK in the soil supplies of available NPK. To find the latter, minus one experiments would suffice as appears from the treatments recommended for SA in Table 2, but factorials give information on PhEmin as well, and the information is statistically more reliable as was shown already in the sixties (Le Mare 1963).

The role of balanced N:P:K proportions seems to remain greatly underrated in soil fertility and plant nutrition research, notwithstanding already half a century ago several publications were issued emphasizing the importance of equilibrated plant nutrition, to be understood as plant nutrition with optimum ratios between N, P, K and other nutrients (Homès 1961; Homès and Verschoor 1966; Beaufils 1971). Despite this recognition of the significance of nutrient ratios, studies on ratios continued to be less popular than research on individual nutrients. In this paper the problem of handling ratios of three nutrients at a same time was solved by application of the concept of crop nutrient equivalents (CNE), and the use of NPK triangles. It made it easy to show and calculate in what direction nutrient inputs should be changed to attain balanced nutrition and by that minimum nutrient wastes. Balanced NPK proportions lead to maximum nutrient use efficiency and thus saves farmers' budgets and environment.

Conclusions

The cause of non-sustainability in the Mekong delta was unbalanced crop nutrition created by too low P applications and decreasing soil P availability in the wet seasons. It is hypothesized that the latter was a result of too short periods between the dry and wet cropping seasons for the replenishment of the labile pool of soil P. Retarded crop growth resulting from P deficiency likely contributed to losses of N and K. Assessment of nutrient uptake in the beginning would have offered early warnings of unbalanced plant nutrition in both long-term experiments, and of losses of N and K in Mekong.

Unsustained soil productivity will not become an issue in Flevoland, as long as N and P are applied. For the time being there is no need to apply K.

The graphs of cumulative yields versus time simplified the illustration of treatment effects and time trends in the long-term experiments. The concept of crop nutrient equivalents and the related NPK triangles proved helpful tools in the valuation of chemical crop and soil analysis, and in designing systems for balanced crop nutrition and thus for sustained soil productivity. In both locations, Mekong and Flevoland, the apparent recovery of fertilizer P was as high as 0.3, and in both cases this could be understood as the result of residual recovery of fertilizer P, that could be assessed with a simple equation for the residual P effect.

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Appendix

One straight line through SA, TA TIA, in case of balanced NPK supplies

Introductory remarks and notations

If the ratios of soil available nutrients (SA) to the amounts of available nutrients required for target yield (TA), so the ratios of SAN/TAN, SAP/TAP and SAK/TAK are q, r and s, respectively, it follows from Eq. 4 that the ratios of TIAN/TAN, TIAP/TAP and TIAK/TAK are (1-q), (1-r) and (1-s). The proportions of SAN : SAP : SAK are q · TAN : r · TAP : s · TAK, which equals q : r : s at balanced nutrient supply where TAN = TAP = TAK if expressed in kCNE. Similarly, the proportions of TIAN : TIAP : TIAK are (1-q) · TAN : (1-r) · TAP : (1-s) · TAK, or (1-q) : (1-r) : (1-s). Hence, if expressed in percentages, FNS, FPS, FKS, the N, P and K fractions of SA, are: $100 \cdot q/(q+r+s)$, $100 \cdot r/(q+r+s)$, and $100 \cdot s/(q+r+s)$, respectively. The sum of (q+r+s) henceforth is denoted by QRS, so FNS, FPS, FKS are 100q/QRS, 100r/QRS, and 100 s/QRS. It follows that the N, P and K fractions of TIA (FNTI, FPTI, FKTI), are: 100 · (1-q)/(3-QRS), 100 · (1-r)/(3-QRS), and 100 · (1-s)/(3-QRS), if expressed in percentages.

The soil supplies of available nutrients seldom are equal for N, P and K. To arrive at balanced nutrient supplies by soil and input, first the most limiting nutrient is applied till the sum of SA+IA of that nutrient has reached the SA level of the second most limiting nutrient. Next these two limiting nutrients are applied till the level of the highest SA. From there onwards all three nutrients are applied in balanced proportions. As a consequence, the NPK composition of nutrient inputs (FNI, FPI and FKI) required for balanced nutrient supplies depend on the level of the target yield (TY). For a given SA, the values of q, r and s become smaller, and those of (1-q), (1-r) and (1-s) become larger with increasing TY and TA. At very large TY, the NPK proportions of TIA approach 1:1:1.

Mathematical prove that SA, TA, and TIA lie on one straight line

In the NPK triangle, the compositions of TIA are found on the extension of the straight line through the points of SA and the centre of the triangle (Fig. 1). To prove this, it is convenient to transform (the points of) the triangle into X and Y coordinates. If the origin of the X-Y diagram corresponds to the N, P and K fractions of 0, 0 and 100%, it follows from simple geometry that at any point in the triangle the value along the Y-axis is equal to SQRT(3) · 0.5 · FN, and that along the X-axis to 0.5 · (100 + FP-FK).

In the X-Y diagram, Y = B · X + C stands for a straight line, and the points of SA, TA and TIA are denoted by X_{SA},Y_{SA}; X_{TA},Y_{TA} and X_{TIA},Y_{TIA}. When these points lie on a same straight line, the slope of the line trough SA and TIA must be equal to the slope of the line trough SA and TA, or

$$B_1 = (Y_{TIA} - Y_{SA})/(X_{TIA} - X_{SA}) = B_2 = (Y_{TA} - Y_{SA})/(X_{TA} - X_{SA}) \quad \text{(A1)}$$

The various parts of Eq. A1 can be expressed in q, r and s.

$$\begin{aligned}
(Y_{TIA} - Y_{SA}) &= 0.5 \cdot \text{SQRT}(3) \cdot (\text{FNI} - \text{FNS}) \\
&= 0.5 \cdot \text{SQRT}(3) \cdot \{100 \cdot (1-q)/(3-\text{QRS}) - 100q/\text{QRS}\} \\
&= 0.5 \cdot \text{SQRT}(3) \cdot (100\text{QRS} - 300q)/\{(3-\text{QRS}) \cdot \text{QRS}\} \\
X_{TIA} &= 0.5 \cdot (100 + \text{FPI} - \text{FKI}) = 0.5 \cdot \{100 + 100 \cdot (1-r)/(3-\text{QRS}) - 100 \cdot (1-s)/(3-\text{QRS})\} \\
&= 0.5 \cdot \{(300 - 100\text{QRS} + 100s - 100r)/(3-\text{QRS})\} \\
X_{SA} &= 0.5 \cdot (100 + \text{FPS} - \text{FKS}) = 0.5 \cdot \{100 + (100r/\text{QRS}) - 100s/(\text{QRS})\} \\
&= 0.5 \cdot (100\text{QRS} + 100r - 100s)/\text{QRS}
\end{aligned}$$

After rearranging the difference (X_{TIA}-X_{SA}) is found to be:

$$X_{TIA} - X_{SA} = 0.5 \cdot \{300 \cdot (s - r)\}/\{(3 - QRS) \cdot QRS\}$$

Hence, B_1, the slope of the line through SA and TIA is:

$$\begin{aligned} &[0.5 \cdot SQRT\ (3) \cdot (100QRS - 300q)/\{(3 - QRS) \cdot QRS\}]/[0.5 \cdot \{300 \cdot\ (s - r)\}/\{(3 - QRS) \cdot QRS\}] \\ &B_1 = \{SQRT\ (3) \cdot (3q - QRS)\}/\{3 \cdot (r - s)\} \end{aligned} \tag{A2}$$

The value of Y_{TA}=0.5 · SQRT(3) · 100/3, and that of X_{TA} is 50. It follows that:

$$Y_{TA} - Y_{SA} = 0.5 \cdot SQRT\ (3) \cdot (100/3 - FNS) = 0.5 \cdot SQRT\ (3) \cdot (100/3 - 100q/QRS), \text{and}$$

$$X_{TA} - X_{SA} = 50 - \{0.5 \cdot (100QRS + 100r - 100s)/QRS\}$$

So, B_2, the slope of the line through SA and TIA is:

$$\begin{aligned} &\{0.5 \cdot SQRT\ (3) \cdot (100/3 - 100q/QRS)\}/[50 - \{0.5 \cdot (100QRS + 100r - 100s)/QRS\}] \\ &B_2 = \{SQRT\ (3) \cdot (3q - QRS)\}/\{3 \cdot (r - s)\} \end{aligned} \tag{A3}$$

Because B_1 in Eq. A2 is equal to B_2 in Eq. A3, it is concluded that the points of SA, TA and TIA lie on the same straight line.

The intercept of the line in the X-Y diagram is:

$$C = Y - B \cdot X \tag{A4}$$

Substitution Y_{TA}, X_{TA} and B2 for Y, X and B in Eq. A4 results in:

$$\begin{aligned} &C = 0.5 \cdot SQRT(3) \cdot 100/3 - \{SQRT(3) \cdot (3q - QRS)\}/\{3 \cdot (r - s)\} \cdot 50 = \\ &= \{50/SQRT(3)\} \cdot \{1 - (3q - -QRS)/(r - s)\} = 28.86751 \cdot \{1 - (3q - QRS)/(r - s)\} \end{aligned}$$

Both regression coefficients, B and C, only depend on q, r and s, so on the NPK composition of SA. Because the position of TA is always in the centre of the triangle, it is easily seen in Fig. 1 that only SA determines the position of the line through SA, TA and TIA.

The points of TWI for different target yields also lie on a straight line (Fig. 1). This line, however, does not go through SA and the centre of the triangle. Its position depends on the position of the line for TIA, and on the recovery fractions (REC) of N, P and K.

The special case of 'Ideal soil fertility' (ISF)

To keep soil fertility at the same level, nutrient outputs must be compensated for by nutrient inputs. When no nutrients are lost by leaching, volatilization or erosion, the only nutrient outputs are the nutrients in the harvested components (e.g. grain and straw) of a crop producing the target yield. The input required in such conditions is known as 'replacement input'. The crop takes up only a fraction (recovery fraction, REC) of the whole input (WI) of nutrients, thus IU = REC · WI, where IU is the uptake from input. In case of replacement input, WI = TU by

definition, and then IU = REC · TU, and SU must equal (1-REC) · TU. The corresponding soil fertility was called 'ideal soil fertility' (ISF), and the values of RECN, RECP and RECK for cereal crops were set at 0.8, 0.1, and 0.6, respectively (Janssen and De Willigen 2006).

For balanced nutrition and replacement input, i.e. at ISF, it holds that TUN = TUP = TUK = WIN = WIP = WIK, when TU and WI are expressed in kCNE. According to QUEFTS calculations, A=1.047 · U in case of balanced nutrition for each of N, P and K, so also TAN = TAP = TAK at ISF. Hence the centre of the NPK triangle represents the composition of TA, TU and WI at ISF. Also here the points of SA, TA and TIA are on one straight line. The proportions of TIUN : TIUP : TIUK of cereal crops, and also the proportions of TIAN : TIAP : TIAK, are at ISF are equal to RECN : RECP : RECK, so to 0.8 : 0.1 : 0.6. This implies that $\mathrm{TIAN} = 100 \cdot 0.8/(0.8 + 0.1 + 0.6) = 53\%$; TIAP=7%, and TIAK=40% of the sum of TIAN, TIAP and TIAK. Similarly, the proportions of SUN : SUP : SUK and of SAN, SAP and SAK at ISF are equal to (1-RECN) : (1-RECP) : (1-RECK)=0.2 : 0.9 : 0.4, and $\mathrm{SAN} = 100 \cdot 0.2/(0.2 + 0.9 + 0.4) = 13\%$; SAP=60%, and SAK=27% of the sum of SAN, SAP and SAK. Figure 1 also presents the these NPK compositions of TIA and SA at ISF. From the calculated compositions it follows that at ISF for each nutrient the difference between TIA and TA is equal to the difference between TA and SA, implying that the positions of TIA and SA are at equal distances from the centre of the triangle.

Approaching ISF by continuous balanced NPK supplies

Many soils are initially relatively rich in K, medium or low in N, and low in P. This is shown for the soil in Fig. 1 of which SAN : SAP : SAK were (in %) 27.7 : 17.6 : 54.7, as was derived from data of Kwale in Kenya (Smaling and Janssen 1993). If such a soil receives nutrient inputs according to balanced nutrition, the NPK composition of SA will change and finally the composition of SA at ISF is reached or at least closely approached. The soil is then low in N, high in P and medium in K (Janssen and De Willigen 2006).

This is because the portions of the input of nutrients that are not taken up by the crop differ for N, P and K. The portions not taken up by the crop partly accumulate in the soil and may partly be lost by leaching, volatilization and erosion. In general, the fraction accumulating in the soil is greatest for P and smallest for N. As a consequence the relative composition of SA increases in P, and decreases in N and K. Finally, the proportions may become equal to those at ISF.

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