

Sustainable agriculture in the tropics: the case of potassium under maize cropping in Togo

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Abstract

The transfers of native and applied K in a rhodic Ferralsol were studied in an agrosystem of southern Togo to propose sustainable cultivation strategies for K in kaolinitic soils. Potassium balance was measured over two years in field conditions under continuous maize cultivation with two K fertilisation levels (0 and 137 kg K ha⁻¹ yr⁻¹). Potassium leaching below the root zone, determined using ceramic cup samplers and Darcy's law, was on average 7.5 kg K ha⁻¹ yr⁻¹ with K fertilisation, *i.e.* 2% of the quantity of K applied, and 4.5 kg K ha⁻¹ yr⁻¹ without. The low leaching values resulted from a K concentration lower than 130 μ M in the soil solution. The low K concentration in the soil solution was related to selective adsorption of K increased by a low content of exchangeable K, with a Gapon selectivity coefficient ranging from 7.9 and 11.5 $M^{-0.5}$. So the level of exchangeable K must first be increased to raise K concentration in the soil solution. The fixation and release of K was analysed using the isotopic exchange method with ⁴²K-ions and compartmental analysis of the kinetics of isotopic exchange. Potassium fixed in a form non available within one year accounted for 78% of the difference between the two treatments. The annual amount of K fertilisation must thus be based on the quantity of K removed in the grain and crop residues, with an extra addition to account for K fixation. Given a crop residue content of 85 kg K ha⁻¹ yr⁻¹ in the fertilised treatment, the return of crop residues is essential if sustainability is to be achieved with traditional cropping systems where little K fertiliser is added.

Introduction

When the fate of K is examined in developing countries in terms of plant growth and sustainability, two main issues - availability of soil K and K exports from the soil - have to be analysed.

In western Africa, crops used to be grown to produce food crops for a few years without fertilizer application and with export of crop residues out of the field. Then the land was returned to fallow for many years to restore part of the fertility. Shifting cultivation is no longer in use, due to increasing population pressure. Nowadays the land is usually cropped every year, sometimes twice a year, without modification of nutrient management. The consequence is widespread nutrient deficiencies. A challenge facing sustainable systems is to maintain crop yields and available nutri-

ent levels in the soil without using too much fertiliser. This requires the fate of nutrients in agrosystems to be properly assessed.

Southern Togo typifies this situation. The population density is over 200 inhabitants km⁻². Fallow periods have almost disappeared. The yield of maize, the main staple food, declines from 2 t ha⁻¹ yr⁻¹ after clearing to less than 1 t ha⁻¹ yr⁻¹ after three to five years of continuous cultivation (Marquette, 1986). It has been recognised that most of the yield decrease was caused by increasing deficiency of major nutrients (Dabin, 1956). This increasing deficiency was explained by leaching, mainly of K, because of the kaolinitic mineralogy of the soil and rainfall was between 800 and 1100 mm yr⁻¹ (Marquette, 1986; Raunet, 1973). However no direct measurement of K leaching in the field was determined.

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The aim of this paper is to describe the fate of K in southern Togo to propose short and long-term strategies capable of meeting yield objectives without depleting available soil K. In this way, a contribution can be made to improve sustainable crop production. To reach this objective, exports of K out of the soil layer which was mined by roots, and K status of bioavailable K were studied in a long-term field experiment with and without K fertilisation.

Materials and methods

Experimental design

The field experiment was carried out at the CIRAD¹ experimental station of Davié (6°22' N, 1°13' E, altitude 50 m). This field was a long-term NPK factorial experiment cropped in maize twice a year since 1976 with two replications for each treatment. The size of each individual plot was 8.0 × 4.5 m. The maize, variety NH1 with a 110-day cycle, was sown twice a year to 42000 plants per hectare. This low density is the optimum for the region because of drought hazards. Average fertilisation during the 1976-1986 period was 0 and 119 kg N ha⁻¹ yr⁻¹ applied as urea, 0 and 23 kg P ha⁻¹ yr⁻¹ applied as triple superphosphate and 0 and 85 kg K ha⁻¹ yr⁻¹ applied as potassium chloride. Potassium applications were 75 kg K ha⁻¹ for the first cropping season and 50 kg K ha⁻¹ for the second season in 1985, 75 kg K ha⁻¹ for both seasons in 1986. Nitrogen was equally split between thinning and tasseling. All fertilisers were broadcast. Crop residues were removed from the field between 1976 and 1980, as farmers do to feed livestock. They were left on the soil surface between 1981 and 1986 to be incorporated once a year before the first cropping season. The fate of native and applied K was studied in the plots which received no K (treatment T0) and K (treatment TK), with N and P fertilisation for both treatments.

The soil was a Ferralsol (FAO-UNESCO, 1989). The main characteristics of the 0-20 cm layer are given in Table 1. The clay content was between 11 to 17% in the topsoil and increased steadily up to 48% in the 140-160 cm layer. The clay mineralogy was mainly kaolinite (80%) with 1.4% to 2% of interstratified illite-smectite minerals.

The annual weather pattern is tropical with two wet seasons, allowing two crops a year. The mean annual rainfall is 1043 mm and the mean annual temperature 27°C. During the two years of the experiments, rainfall (1045 mm in 1985, and 1051 mm in 1986) was close to the annual average.

Soil sampling

Soil samples were taken from each plot of the two replications in 1986. The samples were collected from six sampling points within each plot to a depth of 160 cm. The cores were divided into 0-10, 10-20, 20-30, 30-40, 40-50, 50-60, 60-80, 80-100, 100-120, 120-140 and 140-160 cm depth increments and the 12 depth samples from each depth were bulked.

Determination of K outputs

Leaching

Two ceramic cups (Soil moisture ref. 653×01-B2M2 4.5 cm in diameter) were placed at 30, 60 and 180 cm depths in the two replicates of the T0 and TK treatments, allowing 4 repetitions for each depth. Soil solution samples were extracted on a fortnightly basis by applying a 60 kPa suction for 24 hours; potassium content was determined by flame spectrophotometry. The mean K concentration was calculated for each date and depth.

The water potential was monitored daily using 14 tensiometers installed in the T0 and TK plots. Water fluxes at 180 cm depth were estimated using Darcy's law and suction-conductivity relationships (Poss, 1991). Potassium leaching was calculated on a fortnightly basis for 1985 and 1986 from the water fluxes at 180 cm depth and the mean K concentration in the soil solution. Potassium leaching was estimated over the 1976-1986 period using the average values for K concentrations and a water model (Poss et al., 1988) to calculate the drainage.

K outputs with plant removal

The grain yield was determined each year from 1976 to 1986. The potassium content in grain and crop residues was determined by collecting 10 plants from each of the 2 treatments in each replicate. Plant removal over the 1976-1986 period was estimated from grain yield, harvest ratio, and the average K content in grain and crop residues.

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Table 1. Physico-chemical soil characteristics (average of the 0–10 cm and 10–20 cm layers)

	Fallow	Treatment T0	Treatment TK
	(after 13 years)	(after 11 years of cultivation)	
Clay content (%)	11	13	17
pH (1 M KCl)	5.0 ¹	4.4	4.9
Organic carbon (%)	0.99	0.50	0.62
Exchangeable cations (cmol _c kg ⁻¹)			
Ca	2.1	1.0	1.4
Mg	1.5	0.5	0.6
K	0.20	0.08	0.35
Al	0.00	0.03	0.01
Cation exchange capacity (cmol _c kg ⁻¹)	3.9	2.0	2.7
Extractable P ^a (mg P kg ⁻¹)	40	46	25

^a Extraction at pH 8.5 by 0.5 M NaHCO₃ and 0.5 M NH₄F

Determination of K status in soil samples

Exchangeable cations

Exchangeable cations, K, Ca and Mg were extracted with 1 M ammonium acetate, buffered at pH 7, and were determined using atomic absorption spectrometry.

Gapon selectivity coefficient

The Gapon selectivity coefficient (Gapon, 1933), k_G , was calculated using equation (1):

$$K_{\text{exch}} / (Ca_{\text{exch}} + Mg_{\text{exch}}) = k_G K_{\text{soln}} / (Ca_{\text{soln}} + Mg_{\text{soln}})^{0.5} \quad (1)$$

where exchangeable cations are expressed in cmol_c kg⁻¹, cation concentrations in the soil solution in M and Gapon coefficient, k_G , in M^{-0.5}.

The Gapon selectivity coefficients were calculated using the exchangeable cations and average cation concentrations measured in the soil solution extracted with the ceramic cups in the field.

Bioavailable soil K

Bioavailable K and isotopically exchangeable K

Potassium is taken up by plant roots as K-ions. Potassium uptake depends mainly on three factors: an intensity factor, I, a quantity factor, Q, and a capacity factor, Cap, which describes the variations of the intensity factor when the quantity factor varies (Beckett, 1964). Therefore, bioavailable soil K must be described with experimental parameters representing these three factors. However, K uptake depends also on time, i.e. on the ability of soil particles to release K-ions with time.

The concentration of K-ions is taken as intensity factor (Barber, 1984). The quantity factor is usually

assumed to be NH₄-exchangeable K-ions, although this estimate gives no information about the ability of soil to release K with time.

Experiments were carried out to compare, after labelling of the isotopically exchangeable K, the isotopic composition of K-ions in the soil solution and the K taken up by crops (Fardeau et al., 1979). These experiments involved both short term exchanges in soil solution systems (100 minutes up to 1 day) using ⁴²K ions and long term exchange and K uptake by plants (6 months) using ⁴⁰K. The results proved that the isotopically exchanged K is the K available to crops. Therefore, the parameters determined to describe the isotopically exchanged soil K in soil solution systems in a steady-state can be used to characterise bioavailable soil K.

Theoretical background When a small quantity R of labelled K-ions is added to a soil solution in a steady state, the concentration of K-ions in solution is steady, but the concentration of radioactivity, r_t , decreases with time. The decrease of radioactivity, r_t , with time, t , and whatever the time t , can be described using the Equation (2):

$$r_t/R = r_1/R [t + (r_1/R)^{1/n}]^{-n} + C_K/K_T \quad (2)$$

where r_1 is the radioactivity remaining in the soil solution after the first minute of isotopic exchange, n is an empirical parameter and K_T the total potassium in the soil (Fardeau et al., 1979). The time t is expressed in minutes, C_K in mM and K_T in cmol kg⁻¹.

Considering the values obtained in isotopic exchange experiments for r_1/R , n and C_K/K_T , equation (2) can be simplified, whatever the soil, for t between

1 and 100 minutes:

$$r_t = r_1 t^{-n} \quad (3)$$

or

$$\text{Log} r_t = \text{Log} r_1 - n \text{Log} t \quad (4)$$

The parameters n and r_1/R can be determined by calculating the two parameters of the linear regression between $\text{Log} r_t$ and $\text{Log} t$ using the experimental data obtained between 1 and 100 minutes of isotopic exchange (Morel et al., 1989).

Whatever the time, the isotopic compositions of K exchanged, E_t , and of K in the soil solution, q , are similar:

$$R/E_t = r_t/q \quad (5)$$

where both E_t and q are expressed in $\text{cmol} (\text{kg soil})^{-1}$.

$$q = dC_K/10$$

where d is the 1:d soil:solution ratio and C_K is expressed in mM

$$E_t = dC_K(R/r_t)/10 \quad (6)$$

As the radioactivity in the solution decreases with time, it was concluded (Sheppard, 1962) that the isotopically exchanged K was included in more than one compartment, unlike what was previously assumed from chemical extraction. Using a compartmental analysis, isotopically exchanged K was divided into five compartments (E_1 to E_5) according to their mean transfer time from the soil to the solution (Fardeau et al., 1992). The central compartment, E_1 , which exchanges its K-ions with all the other compartments, consists of the ions exchanged within 1 minute:

$$E_1 = dC_K(R/r_1)/10.$$

The size of E_1 is about 10% higher than 1 M NH_4 OAc exchangeable K (Fardeau et al., 1979; Poss et al., 1991). The other compartments contain ions which can be released in the soil solution through the central compartment, and thus can be taken up by plants roots, between 1 minute and 1 day (E_2), 1 day and 3 months (E_3), 3 months and 1 year (E_4) and over 1 year (E_5).

Experimental procedure Ten grams of soil and 99 ml of deionized water were shaken overnight to reach a steady-state where no net transfer of K-ions appeared between the soil and its solution. One millilitre of water containing a quantity of radioactivity R (between 10

and 100 kBq) was then added to the suspension as ^{42}K . The suspension (1:10 soil:solution) was shaken using a magnetic stirrer and samples were taken after 1, 10, 40 and 100 minutes. The samples were immediately filtered through a $0.01 \mu\text{m}$ filter. The K concentration, C_K , was determined by atomic absorption and the ^{42}K concentration, r_t , was determined by solid scintillation counting.

The n and r_1/R values were determined with equation [4] for the first 100 minutes of isotopic exchange. The quantities E_1 , E_2 , E_3 and E_4 of isotopically exchanged K after 1 minute, 1 day, 3 months and 1 year were determined using Equation (6) and the r_t value was calculated with Equation (2). The size of each compartment was calculated as the difference between the E_t values of two successive times. The size E_5 of the compartment containing the K-ions which can be released in the soil solution in more than 1 year was calculated as the difference between total K, K_T , and $E_1 + E_2 + E_3 + E_4$.

Isotopic exchange was carried out on the soil samples bulked on the 0–30 cm layer and on the soil samples of the 80–100 cm layer.

Results and discussion

Grain yields

Grain yields (Table 2) were near the mean yield over the 1976–1986 period: $1.4 \text{ t ha}^{-1} \text{ yr}^{-1}$ for the T0 treatment and $4.0 \text{ t ha}^{-1} \text{ yr}^{-1}$ for the TK treatment. As the annual rainfall was also near the average, the years 1985 and 1986 can be considered as representative of average conditions for southern Togo.

K fluxes under field conditions

K inputs.

Potassium inputs were K applied with fertilisers and K associated with rainfall (Table 2). Using the annual rainfall and its average concentration, $10 \mu\text{M}$, determined from 8 rain samples collected during 1984 to 1986, the total potassium applied through rainfall was $4.1 \text{ kg K ha}^{-1} \text{ yr}^{-1}$.

K leaching.

Although treatment T0 produced half the yield of treatment TK, the difference in water fluxes at 180 cm depth was only 48 mm in 1985 and 60 mm in 1986 (Table 2).

Table 2. Maize yield, water drainage and potassium balance in 1985 and 1986 (kg K ha⁻¹)

Year Treatment	1985		1986	
	T0	TK	T0	TK
Maize yield (t ha ⁻¹ yr ⁻¹)	2.0	4.8	1.5	4.4
Drainage (mm)	264±85 ^a	216±67	436±141	376±115
Inputs				
Rain	4	4	4	4
Fertiliser (KCl)	0	125	0	150
Outputs				
Leaching	3±1 ¹	4±1	6±1	11±3
Grain	8	23	6	21
(Crop residues)	(10)	(88)	(8)	(81)
Balance				
Crop residues retained	-7	+102	-8	+122
(Crop residues removed)	(-17)	(+14)	(-16)	(+41)

^a Standard error ($p < 0.10$)

This can be explained by evaporation less than 10% higher in TK than in T0. Errors associated with the use of Darcy's law led to a variation coefficient of 30% on the drainage flux (Poss, 1991).

The K concentrations in the soil solution at 30 cm and 180 cm depths were between 20 μM and 50 μM throughout the experiment for treatment T0 (Figures 1 and 2). They were between 30 μM and 60 μM for treatment TK in 1985 and between 50 μM and 120 μM in 1986, with some peaks reaching 130 μM . These peaks of K concentration can be explained by K released from the previous crop at the beginning of the rainy seasons, in April and September. The average K concentration in the soil solution was 30% higher in treatment TK than in treatment T0. On average, K leaching at 180 cm over the two years was 4.5 kg K ha⁻¹ yr⁻¹ for T0 and 7.5 kg K ha⁻¹ yr⁻¹ for TK (Table 2). The apparent leaching of K fertiliser was 3 kg K ha⁻¹ yr⁻¹, 2% of applied K. As a result of the low K concentration in the soil solution, the errors on leaching values ($p < 0.10$) were between 1 and 3 kg K ha⁻¹ yr⁻¹, despite the uncertainty on drainage. In this agro-ecosystem, K leaching below 180 cm was about the same as K added through rainfall and was thus negligible compared to K added. These results agree with published data dealing with the cultivation of various crops in western Africa where K fertilisation was between 30 and 40 kg K ha⁻¹ yr⁻¹. Potassium leaching is usually less than 10% of K applied (Pieri and Oliver, 1986; Van der Pol

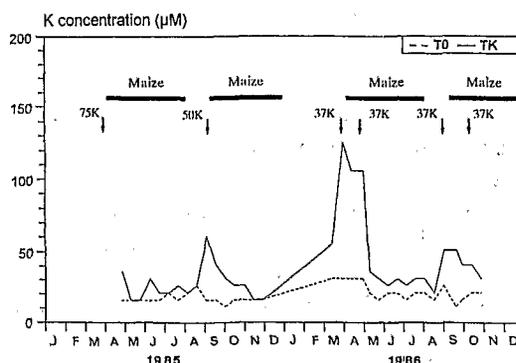


Figure 1. Potassium concentration in the soil solution at 30 cm

and Traore, 1993; Wong et al., 1992). As low losses were observed whatever the rainfall conditions, it can be concluded that the low K leaching was attributable to a low K concentration in the soil solution rather than low drainage.

K uptake and output with maize

Potassium content was 0.40% and 0.48% in the grain, 0.38% and 1.62% in the crop residues (stems, leaves and leaf sheaths) for the T0 and TK treatments, respectively. Potassium fertilisation increased by 20% K content in the grain but by 426% K content in crop residues. Over the years 1985 and 1986 the amount of K was on average 7 and 21 kg K ha⁻¹ in grain and 9 and 85

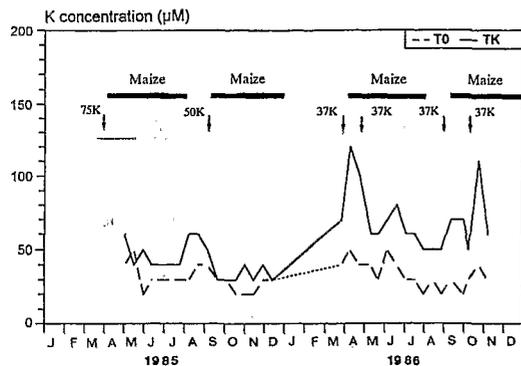


Figure 2. Potassium concentration in the soil solution at 180 cm

kg K ha⁻¹ in crop residues in T0 and TK, respectively (Table 2). As crop residue biomass is higher than grain yield with a K content similar or higher, crop residues always contain more K than the grain.

Potassium exported by the crop over the 12 years of experiment was 354 kg K ha⁻¹ in T0 (100 kg K ha⁻¹ in grain and 254 kg K ha⁻¹ in crop residues) and 640 kg K ha⁻¹ in TK (218 kg K ha⁻¹ in grain and 422 kg K ha⁻¹ in crop residues).

K balance in soils

The K balance in the soil was negative for treatment T0, -7 kg K ha⁻¹ yr⁻¹ on average, with little difference between the two years (Table 2). The balance in the soil was positive in treatment TK, +102 kg K ha⁻¹ in 1985 and +133 kg K ha⁻¹ in 1986. The difference between the two years can be explained by a higher level of fertilisation in 1986. In treatment TK the removal of the crop residues would have considerably reduced the positive balance.

K status in soil samples

NH₄-exchangeable K

The total amount of exchangeable K in the 0-60 cm layer was 217±15 kg K ha⁻¹ in T0, 637±83 kg K ha⁻¹ in TK, compared to 416±29 kg K ha⁻¹ in a plot under fallow. The change in NH₄-exchangeable K in the T0 treatment compared to the fallow was -199 kg K ha⁻¹ in the 0-60 cm soil layer (Figure 3). For this treatment the balance, over the 12 years, between K exported (crop removal and leaching) and K added (rainfall) was -372 kg K ha⁻¹. The export of K with crop residues (254 kg K ha⁻¹) accounted for the most depletion of exchangeable soil K.

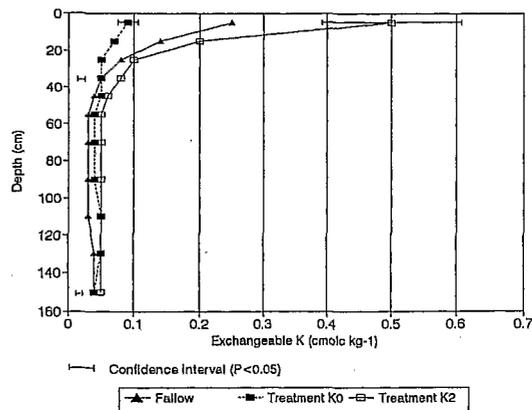


Figure 3. Profiles of NH₄ OAc-exchangeable K

As the exports were higher than the decrease in exchangeable K, some K must have been released from slowly exchangeable soil K compartments. The exact magnitude of release under field conditions remains unknown, as exchangeable K may have increased with time in the fallow treatment. Nevertheless, comparison over the 12 years between the total balance of exchangeable K and K exported with crops shows that K release cannot exceed 14 kg K ha⁻¹ yr⁻¹, an amount of K comparable to K contained in a crop yielding 1.5 t ha⁻¹ (Table 2). This result suggests that the soil has now reached its minimum level of exchangeable K and that it continuously releases K at a low rate. According to Munson (1982) this level must be considered as lower than the critical level whatever the soil type under tropical climates. In these conditions available soil K is a limiting factor to crop production.

The change in NH₄-exchangeable K was +221 kg K ha⁻¹ in the 0-60 cm soil layer of the TK treatment compared to the fallow (Figure 3). Most increases occurred in the upper layers, but some went down to 60 cm depth, although K was applied only to the 0-20 cm soil layer. The balance, over the 12 years, between K exported (crop removal and leaching) and K added (fertiliser and rainfall) was +225 kg K ha⁻¹. The similarity of the results does not exclude a possible fixation of K applied as fertiliser, or simultaneous fixation and release of K-ions.

Gapon selectivity coefficient for K

The k_G values ranged between 7.9 and 11.5 $M^{-0.5}$ irrespective of treatment and depth (Table 3). They are comparable to k_G values observed in laboratory experiments on various kaolinites: between 10 and 20

$M^{-0.5}$ with a K saturation between 4% (Delvaux, 1988) and 10% (Jensen, 1973). Such an affinity cannot be attributable to pure kaolinite (Pedro, 1974).

The correlation between calcium and potassium concentrations was low in the soil solutions from the T0 and TK treatments ($r = 0.24$ for $n = 34$ in treatment T0 at 30 cm) despite a high correlation between calcium and magnesium contents ($r = 0.81$ in the same treatment). This result suggests that specific sites for K adsorption exist in the soil. The affinity of the soil for K can be explained by the presence of small amounts of interstratified clay minerals detected by X-ray diffraction (Poss et al., 1991).

Calculating Gapon coefficients using field data has never been reported. Indeed K in the soil solution was considered to be too far from equilibrium with exchangeable K (Goulding, 1983; Sparks, 1987) and several ions were involved in determining K concentration in solution (Evangelou et al., 1994). As k_G was almost steady for all treatments and depths we can conclude that (i) K-ions in solution were not far from equilibrium with the solid phase; (ii) calcium and magnesium concentrations were, after K saturation, the main factors controlling K-ion concentration in the soil solution; (iii) data observed from field experiments carried out near a steady-state can be used to estimate the K affinity of the soil and to predict the fate of K fertilisers.

Bioavailable soil K determined as the isotopically exchangeable K

The intensity factor (K content in the soil solution C_K) and the quantity factor (instantaneously available soil K, E_1) were about twice as high in TK as in T0 (Table 4). The amount of K isotopically exchangeable in more than one year (E_5 compartment), which is unavailable to crops during a cropping season, was higher in TK than in T0. The amount of K in this compartment accounted for 78% of the difference between T0 and TK. The quantities of K in compartments E_2 to E_4 and the differences between treatments were small compared to the amount of K in the E_1 and E_5 compartments. Thus more K-ions were readily available and more K-ions were fixed in TK than in T0.

It was shown that in this soil about 20% of K added as KCl is fixed and that wetting and drying releases some initially non available K (Poss et al., 1991). The difference between T0 and TK can thus be explained by the fixation of some K added in fertiliser in TK and a release of fixed K in T0.

K cycling in southern Togo: conditions for sustainability

In any sustainable system (i) the production of food and fibre in quantities must be sufficient to satisfy present human requirements and (ii) the ability of soils to produce foods for future generations must be preserved. Applying the sustainability concept to K management in southern Togo involves determining (i) whether food production in southern Togo is sufficient to feed the local population, (ii) whether K is the main limiting factor for crop production, (iii) whether agricultural practices can compromise, in terms of K fertility, the ability of the soil to produce food, and finally (iv) how K must be managed in these agrosystems to reach sustainability.

In Togo, and mainly in the southern part of the country, grain production is lower than the local consumption. Such a form of agriculture cannot be considered as sustainable. To become sustainable, the production of staple food like grain must increase.

In southern Togo it has been recognised for a long time that potassium is the main limiting factor to crop production (Dabin, 1956; Saragoni et al., 1992). The flux of K from the readily bioavailable compartment towards the soil solution can be increased without adding any K using various techniques, like deep ploughing. But the comparison of the profiles of NH_4^+ -exchangeable K for T0 and for the fallow (Figure 3) shows that the rate of release of available soil K from initially non-exchangeable K is too low to maintain a non critical level of bioavailable soil K, even when the uptake is small. When no K was applied, K was a limiting factor to maize grain production, even though maize is a crop with low K requirement. As K uptake from soil cannot be significantly increased, sustainability must be achieved by applying K fertiliser.

Continuous cropping decreased the amount of exchangeable K by 199 kg K ha^{-1} over 11 years in T0 compared to a plot under fallow. Various experiments in the region suggest that when the soil fertility is depleted even high input techniques are not able to restore the initial yields. So the traditional cropping systems are not able to preserve the ability of the soil to produce food.

Maintaining or increasing the level of available soil K is a prerequisite for any sustainable system. In traditional agro-ecosystems of southern Togo, K must mainly be applied to compensate the output in grain and in crop residues, as K leaching and K addition through rainfall can be neglected. In the traditional

Table 3. Gapon selectivity coefficient

	Soil solution			Exchangeable cations				Gapon coefficient $M^{-0.5}$
	K	Ca	Mg	K	Ca	Mg	K/(Ca+Mg) %	
	mM			cmol _c kg ⁻¹				
	30 cm			20-30 cm				
T0	0.037	0.36	0.28	0.05	2.3	0.7	2	11.5
TK	0.058	0.13	0.09	0.10	1.9	0.7	4	10.0
	60 cm			50-60 cm				
T0	0.032	0.40	0.32	0.04	2.1	1.1	1	10.5
TK	0.053	0.39	0.37	0.05	1.9	1.4	1	7.9
	180 cm			140-160 cm				
T0	0.034	0.79	0.52	0.04	2.1	2.0	1	10.4
TK	0.057	0.53	0.26	0.05	1.2	1.3	2	9.9

Table 4. K in soil solution (1:10 soil:water) and in compartments of bioavailable soil K, as determined by isotopic exchange (0-30 cm layer)

	Soil solution	Compartments of bioavailable K				
	C _K μM	E ₁	E ₂	E ₃	E ₄	E ₅
		cmol kg ⁻¹				
T0	15	0.041	0.013	0.010	0.005	0.93
TK	28	0.085	0.005	0.005	0.003	1.03

farming systems in Togo, farm product income does not cover the cost of K fertilisers needed to compensate for K output. In K fertilised treatments, the comparison between the quantities of K in crop residues (85 kg K ha⁻¹ yr⁻¹) and the quantity of exchangeable soil K (637 kg K ha⁻¹) shows that returning the crop residues must be the first objective (Bationo et al., 1993; Pieri and Oliver, 1986; Smaling et al., 1993). When NH₄-exchangeable soil K is relatively high during the first years of cultivation after clearing or fallow, the return of crop residues is critical. The return of crop residues could appear to be less important when the soil has been depleted in bioavailable soil K, because crop residues contain very low amounts of K (9 kg ha⁻¹ K yr⁻¹ in T0). However sustainability implies that food production must satisfy present human requirements. Comparison of the yields of treatments TK and T0 shows that K deficiency limits crop production in treatment T0 and that food production is not sufficient to satisfy human needs. To produce 2 t ha⁻¹ yr⁻¹ of grain, returning the crop residues to the soil would save about 30% of the cost of K fertilisers over the first few years, the percentage rising with increasing biomass production. Finally, whatever the soil, depleted or enriched in

bioavailable soil K, crop residues have to be left in the fields.

After an application of K, the soil is a sink for K-ions applied in the soil solution because of the selectivity of soil particles for K. As the Gapon selectivity coefficient decreases when K saturation increases, the amount of exchangeable K must first be raised to increase the K concentration in the soil solution. Then the amount of K annual fertilisation must be based on the amount of K removed in the grain and crop residues, with an extra 20% to account for K fixation.

Sustainable management of K in developing countries from the tropics, where crop residues have many traditional uses, requires a reduction in the amount of K exported from fields and an increase in the amount of K added in a form available to crops. Potassium in crop residues must be considered, more than in developed countries, as the first and most important K fertiliser for the following crop. The attitude of farmers towards the soil needs therefore to change, with soil fertility being seen as a non-renewable resource rather than as a mine (Van der Pol & Traore, 1993).

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