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RESEARCH ARTICLE

Potassium supplying capacity of some tropical alfisols in southwest Nigeria as measured by intensity, quantity and capacity factors

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Abstract Experiments were conducted in the laboratory, greenhouse and on farmers' fields to determine, the potassium (K) supplying capacity of some soils in Ogun State, Nigeria, using equilibrium parameters as measured by quantity, intensity and activity indices. The result showed that the potassium status of the soils varied widely. Total K varied from 14.2 to 104 cmol kg^{-1} in the green house soils and 46.05 to 89.1 cmol kg^{-1} in the field soils. On the average, exchangeable and solution K constituted 0.39 and 0.09% of the total K, respectively in the greenhouse soils. The potential buffer capacity (PBC), which measures the ability of the soil to maintain the intensity of K in the soil solution, varied from 12.24 to 39.25 ($ML^{-1/2}$). About 50% of the soils studied in the green house and in the field have high PBC indicating slow release of K to the soil solution. The specifically bonded K which constituted the bulk of the labile K (K_L) that is immediately available is generally low. It ranged from 0.10 to 0.29 cmol kg^{-1} with a mean of 0.18 cmol kg^{-1} in the greenhouse soils, and mean of 0.16 cmol kg^{-1} in the field soils. These low values accounted for the appreciable responses to K application by soybean in most of the soils studied. The change in Gibb's free energy (ΔG) values, which measures the intensity of exchangeable K relative to other cations, is moderate in most of the soils. Correlation analysis showed that all the forms of K correlated positively and significantly with soybean dry matter yield at the first cropping harvest. However, soybean K concentration in the first harvest was only positively correlated with available K, exchangeable K, solution K and fixed K ($P < 0.01$). The clay content of the soil is also positively and significantly correlated with K forms. The prediction equation showed that the soil's clay content is a major determinant of labile K, equilibrium activity ration (EAR) and the potential buffering capacity. The EAR is also strongly determined by the ECEC and the K saturation ($R^2 = 0.990$, 0.996, $P < 0.01$). The critical level of soil labile K, available K and specifically bonded K are 0.21, 0.35, and 0.19 cmol kg^{-1}, respectively. Thus, with the use of available K as the index of K fertility, about 50% of the soils are K deficient. Hence potassium fertilization is necessary for enhanced production of soybean in these sites.

Keywords Potassium status · Quantity-intensity-capacity indices · Southwest Nigeria

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Introduction

Clay minerals are primary sources of potassium in the soil. They hold the bulk of mobile potassium and release it when its concentration in the soil solution falls due to plant uptake or to an increase in soil moisture content (Datta and Sastry 1993). Layer silicate micaceous mineral (mica, vermiculite, smectites) and feldspars are sources of K in the soil. Potassium is released from the edge and wedge zones of micaceous minerals and feldspars, because weathering of these minerals start from the edge of the crystal and does not proceed on the whole surfaces. In feldspars the exchange front penetrates further into the particle as weathering proceeds, this portion of K is relatively, weakly bound compared to interlayer K (Bolt et al. 1963).

The presence of K in these various sources has given rise to different forms of K in the soil and these are: (1) water-soluble K which is taken up directly by plants, (2) exchangeable K held by negative charges on clay particles which is releasable to plants, (3) "Fixed" K, is trapped in between layers of expanding lattice clay during weathering and (4) lattice K or mineral K which is an integral part of primary K bearing minerals (Vantaskash and Satyarana 1994). All these forms of K play important role in the K supplying capacity of the soils. However the extent of contribution of each varies with soil type. Consequently K supplying capacity is conceived to include K supplied from soil solution K, exchangeable K and non-exchangeable K forms (Pal and Mukhopadhyay 1992). These forms have given rise to different indices of measuring K availability and there is a dynamic equilibrium existing between them (Udo 1982).

These indices have been variously described by the following parameters. Quantity (Q), Intensity (I) and capacity factors (Beckett 1964a, b). The quantity factor is the total amount of K in the soil, which the plant could draw its K from. Intensity factor (concentration of K in soil solution) is the amount of K that is readily available to the plant while buffering capacity factor is the ability of the soil to release K from non-exchangeable to exchangeable and soluble form, when the K in solution is depleted by crop uptake.

Many soils in Nigeria are deficient in K (Adepetu et al. 1992). Thus, accurate soil test is required to be able to diagnose which of the soils are deficient and which are not. Extractants have been used to determine the plant availability K in the soil or the soil solution hence, K needs of crops.

The use of 1 M NH_4OAC has been the most popular of the extractants. It is assumed to extract all solution K together with not less than 70% of exchangeable K. However, many workers have observed that at times, some soils that test high may respond to K application contrary to expectation. This is an indication that there are other forms of K other than the exchangeable K contributing to K needs of crops. Non-exchangeable K has been shown to also contribute significantly to plant uptake, this has often been ascribed to the fixed K; step K (Surapaneni et al. 2002; Officer et al. 2006). Potassium fixation is a direct consequence of the presence of 2:1 clay minerals. However recent studies in West-Indices and in Nigeria (Agboola and Omueti 1983; Adetunji and Adepetu 1993; Delvaux et al. 1989; Delvaux et al. 1990a, b) have shown that this phenomenon also occurs in tropical soils with insignificant content of 2:1 silicate clays. The mechanism for such has not been elucidated. Therefore in assessing the K supplying capacity, the readily released K and the slow released K portions must be assessed because of the dynamics of water and gas in the soil plant system, rhizosphere processes, etc. Reports of K deficiency in southwest Nigerian soils have been reported by Adetunji and Adepetu (1993), while the exact levels of soil K at which the deficiencies occur cannot be predicted accurately. Hence, in order to improve the reliability of predicting soil K, indices of K availability should be considered.

Accordingly, the use of intensity and quantity factor then becomes imperative. The objectives of this study were to:

Characterize the K-supplying capacity of some Ogun State soils using quantity, intensity and buffering capacity factors.
Describe the relationships between these indices and soil properties.
Determine the relationship between the indices and farm yield.

Materials and methods

Soil sampling

A total of twelve surface soils (0–15 cm) were collected from different locations in Ogun State.

These are Ijale-Papa, Tibo, Olorunda, Ibooro, Imashai, Igoya, Idofa, Ikenne, Kobape, Obalaju, Ago-Iwoye and Ojere. These soils are derived from either sedimentary rock or Basement Complex and they belong to different orders as shown in Table 1.

The soil samples were air-dried, sieved through 4 and 2 mm sieve to remove debris and stone particles. The former reserved for pot trials in the greenhouse while the latter was reserved for laboratory analysis.

Soil analysis

Particles size analysis of the soils was determined by the hydrometer method (Bouyocus 1951). Soil pH was determined using glass electrode in a 1:1 soil–H_2O ratio (Page 1982). The acidity was extracted with 1 N KCl solution and determined by titration with 0.1 N sodium hydroxide solution (Maclean 1965). Organic carbon was determined by the wet digestion suggested by Walkley and Black (1934).

Exchangeable sodium, potassium, calcium and magnesium in the soil samples were extracted with neutral 1 M NH_4OAC. Potassium and sodium in the extract were determined by flame photometry while Ca and Mg were determined by atomic absorption spectrophotometery (Page 1982). Total K in the soil samples was estimated as the sum of available and non exchangeable K while the non-exchangeable K was the sum total of the fixed and mineral K. Fixed K was extracted from the soil by 1 N HNO_3 and estimated as described by Pratt (1965).

Water-soluble K was extracted from 1:2.5 soil–H_2O suspension after 30 min (Maclean 1961). Exchangeable K was obtained by deducting water- soluble K from 1 M NH_4OAC extractable K (Available K). The difference between the non-exchangeable K and the 'fixed' K gave the mineral K (Woodruff 1955). The labile K (K_L) comprises of non-specifically held or immediate sources of available K (K_o) and specifically held K (K_x). The soils with high K_L have the potential to replenish the K concentration in the soil solution under intensive cropping for longer period than soils with low K_L.

Determination of quantity/intensity parameters

The quantity parameters of soils were measured according to the procedure of Beckett (1964c). About 5 g of soil samples were weighed; 50 ml of 0.003 M $CaCl_2$ was added to the soil which already had K solution. The concentration of K ranged between 0.06 and 0.2 M. The soil suspensions were shaken on a reciprocal shaker for 12 h and allowed to stand overnight before filtering. The equilibrium solution was analysed for K and Na using flame photometer. Calcium and Mg were determined titrimetrically using 0.2 M EDTA. The amount of K adsorbed or released by the soils (ΔK) was obtained from the change in the concentration of K in solution (the difference between the initial K and final solution concentration of K). The gain or loss of K+ (ΔK) by the soil solution during the equilibration period constitutes the quantitative term (Q), whereas the cation activity ratio (AR), usually AR^k ($a_k/a_{Ca} + a_{Mg}$), in the equilibrated solution gives the intensity factor (I) of the relationship. The quantity factor is the total amount of K in the soil, which the plant could draw its K from. Intensity factor is the amount of K that is readily available to the plant while buffering capacity factor is the ability of the soil to release K from non-exchangeable to exchangeable and soluble form, when the intensity factor is depleted by crop uptake. They were plotted taking $\pm\Delta k$ on *y*-axis and AR^k ($a_k/a_{Ca} + a_{Mg}$) on the *x*-axis. The typical Q/I parameters were determined, AR^K was calculated from the measured concentrations of Ca^{2+}, Mg^{2+} and K^+ corrected to their respective activities. Ionic strengths were determined by the electrical conductivity relationship, and were used to calculate the activity coefficients. A simple linear regression equation was developed for the linear range of the Q/I plots to compare soils and to arrive at a value for potential buffering capacity (PBC^K). PBC is a measure of the ability of the soil to replenish used K. Linear regression equation was also developed for the deviation from linearity towards the ordinate axis to obtain AR^K (intensity factor).

Determination of critical level

The critical level of K was determined to predict the possibility of having economic responds to K fertilizer application or K need of the soil samples using the statistical procedure described by Cate and Nelson (1971).

Table 1 Some physicochemical properties of the experimental sites and farms

Sites	pH	Physicochemical properties of soils		Na (cmol $_{(+)}$ kg^{-1})	Ca (cmol $_{(+)}$ kg^{-1})	Mg Na (cmol$_{(+)}$ kg^{-1})	Acidity Na (cmol $_{(+)}$ kg^{-1})	ECEC Na (cmol $_{(+)}$ kg^{-1})	Soil classification
		Organic C (%)	Clay (%)						
Ijale Papa	5.61	2.63	9.20	0.08	0.40	0.16	0.13	1.19	Kandic Paleustalf
Olorunda	6.38	2.76	3.60	0.01	0.60	0.16	0.04	1.45	Kandic Paleustalf
Tibo	5.19	1.29	9.60	0.07	0.30	0.15	0.18	0.88	Kandhaplic-Haplustalf
Ibooro	4.33	2.36	7.60	0.07	0.60	0.15	0.64	1.29	Kandhaplic-Haplustalf
Imashai	6.80	1.99	10.80	0.06	0.70	0.16	0.17	1.39	Kandic-Paleustalf
Obaloju	5.69	1.69	6.60	0.08	0.50	0.16	0.02	0.96	Arenic Paleustalf
Ikenne	5.23	2.23	2.40	0.07	0.40	0.19	0.03	1.12	Kandic Paleustalf
Igoya	4.93	2.17	14.40	0.08	1.11	0.19	0.41	1.94	Kandhaplic-Haplustalf
Idofa	5.93	1.20	8.40	0.06	0.60	0.14	0.06	1.96	Arenic Paleustalf
Ago-Iwoye	5.16	1.50	5.60	0.05	0.40	0.15	0.01	0.80	Kandhaplic-Haplustalf
Kobape	5.79	1.06	5.40	0.07	0.50	0.15	0.41	1.35	Kandic Paleustalf
Ojere	5.71	1.09	4.40	0.11	0.15	0.16	0.08	0.87	Arenic Paleustalf
Mean	5.56	1.83	7.33	0.07	0.52	0.16	0.18	1.27	
SD±	0.66	0.61	3.38	0.02	0.24	0.02	0.20	0.39	
Farms									
Ojere	5.98	2.56	6.40	0.06	0.80	0.15	0.07	1.76	Kandic Paleustalf
Alabata1	5.71	1.45	5.20	0.06	0.90	0.17	0.12	1.69	Kandic Paleustalf
Alabata2	6.56	0.97	2.80	0.04	0.60	0.16	0.08	1.24	Kandic Paleustalf
Adigbe	6.79	0.19	0.40	0.03	0.70	0.16	0.10	1.39	Kandic Paleustalf
Oluwo	5.84	0.90	11.60	0.07	0.98	0.18	0.14	1.69	Kandic Paleustalf
Mean	6.18	1.21	5.28	0.05	0.80	0.16	0.10	1.55	
SD±	0.47	0.88	4.22	0.02	0.15	0.01	0.03	0.23	

Pot experiment

Soils from 12 different locations representing the major soil series of south-west Nigeria were collected for the study. Two kilograms of the sieved soil samples were weighed into each pot. Two rates of K (0 and 100 mg kg^{-1}) were applied to the pots. All treatments received initially 20 mg N kg^{-1} as NH_4NO_3 and 50 mg P kg^{-1} as $NaHPO_4.12H_2O$. The pots were arranged in a green house, the design was a randomized complete block design with three replicates.

Three seeds of soybean (*Glycine max*) were planted in each pot, which were later thinned to two seedlings per pot. Five cycles of the crop of 4 weeks each were grown. At 4 weeks, the soybean cultivar used attained about 80% of its vegetative growth at this period. At the end of each cycle, soil samples were taken for the determination of K forms the whole plant tops were harvested, oven dried at 60°C for 48 h. A portion of the plant tissue was milled and digested with H_2SO_4–H_2O_2 mixture and K content of the soil and plant samples were determined by flame photometry.

Field experiment

The result obtained from the greenhouse experiment was verified in five farmers' fields representing the major soil series used for the pot experiment. A plot of 5 m × 5 m each of five soybean farms selected at different locations in Abeokuta. The five farms were in Ojere, Alabata1, Alabta2, Adigbe, Oluwo. These sites fall in the derived savanna ecological zones of Ogun State, Nigeria. The farm is a derived savanna ecosystem with a bimodal rainfall pattern (April–July and September–October) and an annual average amount of 1,000–1,500 mm and temperature of 25–27.5°C, the soil is majorly alfisol on basement complex rock. The selected plots were analyzed for all K forms and the grains were harvested to determine the yield per hectare. The forms of K of the plots were correlated with the yield.

Data analysis

The mean and standard deviation of the values for the various soils were calculated. Correlation and regression analyses among soil and agronomic parameters were done using SAS package (SAS 2000).

Results

Table 1 shows some relevant physicochemical properties of the soil. The pH values of the soil ranged from 4.33 to 6.80 while the average was 5.56. The mean pH value of the soils used for greenhouse study was lower than those of the farm soils (6.18). There were some variation in the organic carbon content of the soils, as indicated in the standard deviation values. The average value of the organic carbon of the soils was higher than those from the farms. As much as 14.40% clay was recorded in Igoya while the highest amount of clay among the farm soils was observed in Oluwo. Generally, the amount of exchangeable cations for both greenhouse and farm soils were in the order Ca > Mg > Na. Taxonomic classification of the soil (Table 1) shows that they belong to the order Alfisols with kaolinite being one of the major minerals in the soils. The potassium status of the experimental soils and farms is shown in Table 2. The order of abundance of the K forms in the soils is mineral K > exchangeable K > fixed K > solution K. The total K in the soils ranged from 14.22 cmol kg^{-1} in Ibooro to 103.94 cmol kg^{-1} in Idofa with a mean value of 67.08 cmol kg^{-1}. The solution K constitutes an average of 0.09% of the total K and ranged from 0.02 to 0.09 cmol kg^{-1}. The exchangeable K of the soil varied slightly with a mean value of 0.26 cmol kg^{-1}, it constitutes 0.39% of the total K. These values were lower than the values for the available K, which constitutes about 0.46% of the total K. The fixed K values ranged from 0.01 to 0.21 cmol kg^{-1}. It is about 0.15% of the total K. The mineral K values of the soils were similar, constituting 99.5% of the total K. For the farm soils, the available K, exchangeable K, solution K and fixed K constitutes 0.70, 0.64, 0.06, and 0.22% of the total K respectively. The total K values of the soils ranged from 46.1 cmol kg^{-1} in Alabata[1] to 89.1 cmol kg^{-1} in Oluwo farm.

Table 3 shows the potassium indices derived from the quantity—intensity isotherms of the soils. The equilibrium activity ratio (ARoK) is the point at which no K exchange takes place and this was

Table 2 Potassium status of the experimental sites and farms

Sites	Exch. K (cmol $_{(+)}$ kg^{-1})	Solution K (cmol $_{(+)}$ kg^{-1})	Avail K (cmol $_{(+)}$ kg^{-1})	Mineral K (cmol $_{(+)}$ kg^{-1})	Fixed K (cmol $_{(+)}$ kg^{-1})	Non Exch. K (cmol $_{(+)}$ kg^{-1})	Total K (cmol $_{(+)}$ kg^{-1})
Ijale Papa	0.34	0.08	0.42	56.16	0.21	56.37	56.79
Olorunda	0.60	0.04	0.64	63.60	0.12	63.72	64.36
Tibo	0.10	0.08	0.18	89.62	0.14	89.76	89.94
Ibooro	0.11	0.02	0.13	13.99	0.10	14.09	14.22
Imashai	0.42	0.03	0.45	53.48	0.14	53.62	54.07
Obaloju	0.12	0.09	0.21	17.78	0.01	17.79	18.00
Ikenne	0.40	0.03	0.43	76.60	0.01	76.60	77.03
Igoya	0.09	0.06	0.15	76.52	0.01	75.52	75.67
Idofa	0.28	0.07	0.35	103.49	0.10	103.59	103.94
Ago-Iwoye	0.14	0.05	0.19	95.04	0.06	95.10	95.29
Kobape	0.13	0.09	0.22	90.81	0.08	90.81	91.11
Ojere	0.35	0.02	0.37	64.00	0.20	64.20	64.57
Mean	0.26	0.06	0.31	66.76	0.10	66.76	67.08
SD±	0.17	0.03	0.16	28.50	0.07	28.46	28.48
Farms							
Ojere	0.67	0.01	0.68	69.32	0.20	69.53	70.21
Alabata1	0.41	0.03	0.44	45.46	0.15	45.61	46.05
Alabata2	0.30	0.06	0.36	52.46	0.12	52.58	52.94
Adigbe	0.31	0.09	0.40	55.49	0.10	55.79	56.19
Oluwo	0.30	0.02	0.32	88.64	0.14	63.14	89.10
Mean	0.40	0.04	0.44	62.27	0.14	57.33	62.90
SD±	0.16	0.03	0.14	17.10	0.04	9.29	17.09

obtained by extrapolation of K at the origin (0) of the graph. The ARoK values varied among the soils. The value ranged from 1.15 cmol kg^{-1} in Tibo to 3.30 cmol kg^{-1} in Olorunda, with an average value of 2.35 cmol kg^{-1}. The values for the farm soils varied slightly though the average value was higher than those of the experimental soils. The soil labile K, is next in magnitude to the ARoK. It varied slightly in the experimental soils. However, the mean values recorded in the farm soils are higher. Non-specifically bonded K (K_o) ranged from 0.01 to 0.06 cmol kg^{-1} and from 0.09 to 0.18 cmol kg^{-1} for the experimental soils and farm soils, respectively. Their corresponding average values were 0.03 and 0.13 cmol kg^{-1}. The specifically bonded K (K_x) of the soils had the average value of 0.18 cmol kg^{-1} for the experimental soil and 0.16 cmol kg^{-1} for the farms. The trend in the values of the K potential (K pot) were similar to other parameters. However, the potential buffering capacity of the soils were higher in the experimental soils than the soils from the farms. Change in free energy shows the intensity of exchangeable K at a given level relative to other cations was relatively high in Tibo (4,698 kcal), Ibooro (4,819 kcal) and Ago-Iwoye (4,518 kcal). Other soils had values higher than 2,000 kcal. Similar high values were recorded for the farm soils. The response of soybean plants to K fertilization under greenhouse conditions is presented in Tables 4 and 5. In Table 4, the responses to K fertilization as measured by the dry matter yield were greater in the first harvest for all the soils. Generally, there was an increase in dry matter yield as a result of K fertilization in all the soils, with the average relative yield being 77.09% in the first harvest. There was a sharp decrease in the plant responses in the 2nd, 3rd, 4th and 5th harvests, with the corresponding relative yield values being 66.5, 57.9, 59.3 and 64.3%, respectively. Potassium concentration of the soybean plants is shown in Table 5. It was observed that the values varied among the soils

Table 3 Potassium indices of the experimental sites and farms derived from quantity/intensity isotherms

Sites	ARoK (cmol $_{(+)}$ kg^{-1})	K_L (cmol $_{(+)}$ kg^{-1})	K_o (cmol $_{(+)}$ kg^{-1})	K_x (cmol $_{(+)}$ kg^{-1})	kpot (cmol $_{(+)}$ kg^{-1})	PBC (ML^{-1})$^{1/2}$	ΔG (kcal)
Ijale Papa	2.90	0.24	0.04	0.20	0.99	16.60	2,637
Olorunda	3.30	0.33	0.04	0.29	0.36	12.24	2,957
Tibo	1.15	0.16	0.03	0.13	1.41	38.00	4,698
Ibooro	2.00	0.12	0.02	0.10	0.75	39.09	4,819
Imashai	2.70	0.29	0.02	0.27	0.24	19.38	2,460
Obaloju	2.80	0.23	0.06	0.17	1.08	21.50	2,250
Ikenne	3.20	0.27	0.03	0.24	0.27	17.50	2,880
Igoya	2.00	0.11	0.01	0.10	2.36	32.00	3,467
Idofa	2.80	0.21	0.02	0.19	1.28	15.29	2,549
Ago-Iwoye	1.20	0.17	0.02	0.15	0.46	39.25	4,518
Kobape	2.00	0.20	0.02	0.18	0.91	22.86	2,433
Ojere	2.20	0.23	0.04	0.19	2.68	20.62	2,063
Mean	2.35	0.21	0.03	0.18	1.07	24.53	3,144
SD±	0.71	0.07	0.01	0.06	0.78	9.86	994
Farms							
Ojere	3.20	0.20	0.09	0.11	2.03	22.50	2,880
Alabata1	2.50	0.40	0.14	0.24	2.86	11.90	2,193
Alabata2	3.50	0.26	0.12	0.14	0.07	19.10	3,102
Adigbe	2.60	0.16	0.11	0.05	3.75	18.33	2,362
Oluwo	3.00	0.42	0.18	0.24	0.07	11.29	2,721
Mean	2.96	0.29	0.13	0.16	1.76	16.62	2,652
SD±	0.42	0.12	0.03	0.08	1.65	16.62	372

ARoK, activity ratio; KL, Labile K; K_o, non specifically bonded K; K_x, specifically bonded K; kpot, K potential; PBC, potential buffering capacity; ΔG, change in free energy

for both fertilized and unfertilized pots. The results indicate that there was a sharp decrease in the K concentration of the plants as the harvest cycle increased. For the fertilized pots, an average of 56% reduction was recorded at the 5th harvest, while the reduction in value was just 36% at the 3rd harvest. Similar trend was observed in the unfertilized pots. Table 6 shows that all the forms of K correlated positively and significantly with soybean dry matter yield at the first harvest. Solution K and fixed K correlated significantly with the dry matter yield at the 3rd and 4th harvest while the correlation between soybean dry matter yield and non-exchangeable K and mineral K were positive and significant at the 5th harvest ($r = 0.618$ and 0.610, $P < 0.05$). However, the correlation of the K forms and the concentration of K in soybean (Table 7) shows that the concentration of K in the first harvest was only positively correlated with available K, exchangeable K, solution K and fixed K ($P < 0.01$). Similar trend was observed at the second, third and fifth harvest ($P < 0.01$). The correlation between the quantity-intensity parameters (table not shown) are all positive and significant ($P < 0.01$). The clay content of the soil is also positively and significantly correlated with these parameters. In Table 8, the prediction equation shows that the soil's clay content is a major determinant of labile K, equilibrium activity ratio (EAR) and the potential buffering capacity. The EAR is also strongly determined by the ECEC and the K saturation ($R^2 = 0.990$, 0.996, $P < 0.01$). Table 9 shows that field grain yield of soybean correlated significantly with all the K forms investigated. However, the highest correlation values were recorded in available K, Exchangeable + fixed K, solution K + fixed K and specifically bonded K.

Tables 10, 11 and 12 shows the determination of the critical levels for soil labile K, available K

Table 4 Effect of potassium fertilizer on dry matter yield (g/pot) of soybean

Soils	1st Harvest			2nd Harvest			3rd Harvest			4th Harvest			5th Harvest		
	k_0	K_{100}	Relative Yield (%)	k_0	K_{100}	Relative Yield (%)	k_0	K_{100}	Relative Yield (%)	k_0	K_{100}	Relative Yield (%)	k_0	K_{100}	Relative Yield (%)
Ijale Papa	1.63	1.80	10.43	0.30	0.36	20.00	0.30	0.35	16.67	0.29	0.33	13.79	0.26	0.30	15.38
Olorunda	1.60	1.15	−28.13	0.40	0.44	10.00	0.35	0.44	25.71	0.30	0.40	33.33	0.18	0.25	38.89
Tibo	1.24	2.94	137.10	0.43	0.82	90.70	0.33	0.82	148.48	0.29	0.70	141.38	0.15	0.60	300.00
Ibooro	0.98	2.50	155.10	0.48	0.94	95.83	0.38	0.94	147.37	0.33	0.60	81.82	0.27	0.39	44.44
Imashai	1.72	1.76	2.33	0.29	0.33	13.79	0.29	0.33	13.79	0.25	0.31	24.00	0.20	0.22	10.00
Obalaju	1.20	1.74	45.00	0.45	0.54	20.00	0.35	0.54	54.29	0.30	0.47	56.67	0.23	0.37	60.87
Ikenne	1.25	1.29	3.20	0.28	0.39	39.29	0.26	0.39	50.00	0.24	0.30	25.00	0.19	0.20	5.26
Igoya	1.46	2.94	101.37	0.34	0.85	150.00	0.30	0.85	183.33	0.28	0.69	146.43	0.19	0.43	126.32
Idofa	0.64	0.84	31.25	0.46	0.67	45.65	0.36	0.67	86.11	NA	0.50	NA	0.12	0.33	175.00
Ago-Iwoye	1.20	2.16	80.00	0.36	0.85	136.11	0.36	0.85	136.11	0.30	0.48	60.00	0.20	0.39	95.00
Kobape	1.25	1.69	35.20	0.47	0.60	27.66	0.37	0.60	62.16	0.28	NA	NA	0.23	0.47	104.35
Ojere	1.90	2.00	5.26	0.42	0.88	109.52	0.32	0.88	175.00	0.24	0.45	87.50	0.18	0.20	11.11
Mean	1.34	1.90	48.18	0.39	0.64	63.21	0.33	0.64	91.59	0.28	0.48	66.99	0.20	0.35	82.22
SD±	0.34	0.66	28.79	0.07	0.23	18.75	0.04	0.23	19.38	0.09	0.19	44.63	0.04	0.12	23.42

NA data not available; Relative yield = $(Y_f - Y_o)/Y_o$, *100 where Yf is the yield in the fertilized treatment ($K = 100$) and Y_o the yield in the control ($K = 0$)

Table 5 Potassium concentration (mg kg^{-1}) in soybean plant

Soils	1st Harvest		2nd Harvest		3rd Harvest		4th Harvest		5th Harvest	
	k_0	K_{100}	k_0	K_{100}	k_0	K_{100}	k_0	K_{100}	k_0	K_{100}
Ijale Papa	0.17	0.19	0.13	0.17	0.09	0.14	0.14	0.1	0.07	0.09
Olorunda	0.19	0.20	0.16	0.18	0.13	0.15	0.11	0.12	0.1	0.11
Tibo	0.14	0.22	0.1	0.19	0.08	0.16	0.08	0.14	0.08	0.13
Ibooro	0.17	0.24	0.14	0.13	0.12	0.16	0.1	0.16	0.1	0.14
Imashai	0.16	0.29	0.13	0.21	0.11	0.19	0.09	0.16	0.07	0.11
Obaloju	0.14	0.25	0.09	0.12	0.08	0.16	0.06	0.14	0.04	0.11
Ikenne	0.15	0.24	0.11	0.16	0.1	0.13	0.08	0.1	0.11	0.12
Igoya	0.16	0.4	0.12	0.2	0.11	0.13	0.09	0.11	0.06	0.07
Idofa	0.15	0.19	0.15	0.23	0.11	0.16	0.1	0.11	0.09	0.1
Ago-Iwoye	0.15	0.26	0.09	0.19	0.08	0.16	0.19	0.12	0.08	0.09
Kobape	0.09	0.29	0.19	0.21	0.17	0.19	0.14	0.17	0.11	0.12
Ojere	0.21	0.28	0.11	0.18	0.1	0.16	0.09	0.11	0.05	0.09
Mean	0.16	0.25	0.13	0.18	0.11	0.16	0.11	0.13	0.08	0.11
SD±	0.03	0.06	0.03	0.03	0.02	0.02	0.03	0.02	0.02	0.02

Table 6 Relationships between potassium forms and soybean dry matter yield

Forms of K	1st Harvest	2nd Harvest	3rd Harvest	4th Harvest	5th Harvest
Available K	0.878**	−0.483	0.156	0.878**	−0.222
Exchangeable K	0.918**	−0.390	−0.093	0.281	0.415
Solution K	0.677*	0.638*	0.950**	0.968**	0.036
"Fixed" K	0.713**	0.307	0.755**	0.774**	0.180
Non-exchangeable K	0.814**	0.083	0.588	0.268	0.618*
Mineral K	0.776**	0.286	0.174	0.268	0.610*

* 5% Significant level

** 1% Significant level

Table 7 Relationships between potassium forms and concentration of K in soybean

Forms of K	1st Harvest	2nd Harvest	3rd Harvest	4th Harvest	5th Harvest
Available K	0.988**	0.603*	0.661*	0.234	0.810**
Exchangeable K	0.870**	0.628*	0.776*	0.326	0.968**
Solution K	0.932**	0.647*	0.618*	0.619*	0.745**
Fixed K	0.911**	0.162	0.253	0.753**	0.313
Non-exchangeable K	0.281	0.001	0.959**	0.399	0.360
Mineral K	0.283	0.001	0.956**	0.401	0.359

* 5% Significant level

** 1% Significant level

and specifically bonded K. It was observed in Table 11, that the critical level of soil labile K is 0.21 cmol kg^{-1} while that of soil available K (Table 11) was 0.35 cmol kg^{-1}. The critical value for the specifically bonded K (Table 12) was 0.19 cmol kg^{-1}.

Table 8 Prediction equations between quantity-intensity parameters and some soil properties

Y-variable	*X*-variable	R^2	Prediction equation
Labile K	Clay	0.636*	$Y = -0.067 + 0.044X$
Equilibrium activity ratio	Clay	0.760**	$Y = 1.45 + 0.435X$
Equilibrium activity ratio	ECEC	0.990**	$Y = -0.211 + 3.93X$
Equilibrium activity ratio	K saturation	0.996**	$Y = 0.138 + 0.005X$
Potential buffering capacity	Clay	0.656*	$Y = 0.100 + 0.028X$

* 5% Significant level

** 1% Significant level

Table 9 Correlation between K forms and field grain yield of soybean

K-forms	Correlation coefficient
Exchangeable K	0.884**
Non-exchangeable K	0.828**
Available K	0.940**
Fixed K	0.713**
Exchangeable K + fixed K	0.914**
Solution K	0.856**
Solution K + fixed K	0.920**
Intensity factor	0.830**
Quantity factor	0.630*
Total labile K	0.962**
Specifically bonded K	0.930**
Non specifically bonded K	0.761*
PBC	0.884**
ΔG	0.904**

* 5% Significant level

** 1% Significant level

Discussion

Soil properties

The soils were slightly acidic and coarse textured. The organic carbon content was moderate in most of the soils. The high clay content in some of the soils might be indicative of having more K bearing minerals than others; this will replenish the solution K when there is K depletion. Available K was high in some of the soils; this implies that slight or no response to K fertilizer might be observed in these soils. However, the mean value of available K falls within the ranges of 0.04–0.34 cmol kg^{-1} and 0.10–0.97 cmol kg^{-1} reported by Wild (1971) and Agboola and Omueti (1983), for the savannah soils of Nigeria and 0.08–2.09% reported for southwest Nigeria soils (Fagbami et al. 1985). The high values of some of the soils may be due to the yearly application of fertilizer, plant residues and manures. The short range variability in the amount of available K is expected in agricultural fields (Morton et al. 2000), however the spatial variability of less available forms of K has rarely been explained in literature (Officer et al. 2006).

Potassium forms

The exchangeable K contributes only 0.39% to the total K. This value is lower than the value obtained by Adepetu et al. (1992), they observed that exchangeable K contributes only 1.06% of the total K in southwestern Nigeria. The solution K status appeared to be lower and could be attributed to leaching losses due to the coarse texture of the soils. The climate of the area is characterized by a bimodal distribution and high rainfall amounts (1,000–1,500 mm/year). Similar result was reported by Chammuah (1987). The soils have the greater part of their available K in the exchangeable form. This is slightly contrary to the observations of Agboola and Omueti (1983), who observed that solution K in soils of northern Nigeria accounts for 53.6% of the available K. The difference might be due to the increased evapotranspiration in northern Nigeria that could have enhanced the upward movement of potassium salts in the drier ecosystem. But this study shows that solution K is only about 29% of the available K. The rate of exchange between solution and exchangeable K forms has been reported to be diffusion controlled and strongly dependent on clay mineralogy (Benipal et al. 2006). The total K is high

Table 10 Relationships between relative dry matter yield and labile potassium concentration of soils using the two-class model of Cate and Nelson technique

Relative yield (%)	Soil labile K (cmol $_{(+)}$ kg^{-1})	Postulated critical level between values	Class sum of squares	R^2
39.20	0.10			
49.70	0.11	0.10–0.11	2834.57	0.36
55.40	0.16	0.16–0.17	3774.06	0.49
66.67	0.17	0.17–0.19	4079.18	0.52
68.90	0.19	0.19–0.20	4472.46	0.57
73.90	0.20	0.20–0.21	4730.66	0.61
79.80	0.21	0.21–0.23	4785.82	0.62
87.90	0.23	0.23–0.24	4460.56	0.57
90.60	0.24	0.24–0.27	4205.96	0.54
96.90	0.27	0.27–0.29	3763.27	0.48
97.70	0.29	0.29–0.33	3968.40	0.51
139.13	0.33			

Relative yield = (yield of minus K pots/yield of plus K pots) × 100

Table 11 Relationships between relative dry matter yield and available potassium concentration of soils using the two-class model of Cate and Nelson technique

Relative yield (%)	Soil available K (cmol $_{(+)}$ kg^{-1})	Postulated critical level between values	Class sum of squares	R^2
39.20	0.13			
49.70	0.15	0.13–0.15	2834.57	0.36
55.40	0.18	0.15–0.18	3774.06	0.49
66.67	0.19	0.18–0.19	4079.18	0.52
68.90	0.21	0.19–0.21	4472.46	0.57
73.90	0.22	0.21–0.35	4730.66	0.61
79.80	0.35	0.22–0.35	4785.82	0.62
87.90	0.37	0.35–0.42	4460.56	0.57
90.60	0.42	0.37–0.42	4205.96	0.54
96.90	0.43	0.42–0.43	3763.27	0.48
97.70	0.45	0.43–0.45	3968.4	0.51
139.13	0.64			

Relative yield = (yield of minus K pots/yield of plus K pots) × 100

in all the soils and could be attributed to the soils containing K bearing minerals. The total K values of 67.08 and 62.90 cmol kg^{-1} are above the range of 0.77–35.8 cmol kg^{-1} reported by Sobulo (1973) in some Nigerian soils. The soils belong to different local series as: Balogun, Iregun, Iwo and Apomu but the distribution pattern of different forms of K is identical. Perhaps, these soils might have undergone similar stages of weathering, though they bear different kinds of parent material. Ramamoorthy and Velaguthum (1978), have reported that the distribution of K in soils follows a definite geomorphic pattern and relates more to the conditions of weathering of potash bearing minerals.

Quantity/intensity parameters

The Q/I relationship depicts the capacity of a soil system to maintain a certain level of K in solution and gives visual representation of how the level of K in

Table 12 Relationships between relative dry matter yield and available potassium concentration of soils using the two-class model of Cate and Nelson technique

Relative yield (%)	Soil specifically bonded K	Postulated critical level between values	Class sum of squares	R^2
39.20	0.09			
49.70	0.10	0.10–0.13	2834.57	0.36
55.40	0.13	0.13–0.15	3774.06	0.49
66.67	0.15	0.15–0.17	4079.18	0.52
68.90	0.17	0.17–0.18	4472.46	0.57
73.90	0.18	0.18–0.19	4730.66	0.61
79.80	0.19	0.19	4785.82	0.62
87.90	0.19	0.19–0.20	4460.56	0.57
90.60	0.20	0.20–0.24	4205.96	0.54
96.90	0.24	0.24–0.27	3763.27	0.48
97.70	0.27	0.27–0.29	3968.4	0.51
139.13	0.29			

Relative yield = (yield of minus K pots/yield of plus K pots) × 100

solution is related to the amount of K available in the exchangeable and soluble forms (Evangelou et al. 1994). Equilibrium activity ratio (ARoK) measures the availability or intensity of labile K in the soil. It measures the binding strength of labile K in soil (Schindler et al. 2005). The greater the AROK value, the greater the amount of plant available K, similar trend was observed in this study. The soils with high ARoK also gave high labile K, which is the K readily available to the plant when solution K is depleted. Labile K is the part of the fixed K that replenishes the solution and exchangeable K, if they are depleted, due to plant uptake of soil solution dilution. This observation supports the report that ARoK indicates the status of the immediately available K and therefore regulates the exchange of K from the exchangeable site of the mineral complex to solution phase Beckett 1964b). The ARoK values obtained in these soils are well above the minimum of 5×10^{-4} $ML^{-1})^{1/2}$ proposed by Beckett and Webster (1971). This might be attributed to higher ionic strength of K^+ in comparison with Ca^{2+} and Mg^{2+} in soil solution. The mineralogy of the experimental soils might have also differed from those used by Beckett and Webster (1971). The labile K (K_L) comprises of non-specifically held or immediate sources of available K (K_o) and specifically held K (K_x). The soils with high K_L have the potential to replenish the K concentration in the soil solution under intensive cropping for longer period than soils with low K_L. Low values were observed for K_o in the soils. Differences in the K_o values of these soils might be ascribed to the nature and quantity of clay minerals in the soils. Similar observations were made by Rupa et al. 2003. The K_o values in the greenhouse and farms were below the amount of exchangeable K in the samples. This agrees with the findings of Beckett and Nafady (1967). They reported that a part of exchangeable K does not contribute to K_o value. Potassium depletion in all the pots under successive cropping is an indication of continuous nutrient stress on the soil system to meet the K requirement of soybean.

Potential buffering capacity (PBC^K) of the soil is a measure of the ability of the soil to maintain the intensity of K in the soil solution or a given AR_OK as the ΔK is increased or decreased and is represented by the linear part of Q/I curve. A soil with a large slope or PBC will have a greater capacity to maintain the activity ratio. High PBC^K values were observed in some soils while others were low; this explains why some of the available K in the soils was also high and low, respectively. This indicated that soils of high PBC have enough K in reserve to replenish used K by crops while those of low PBC will only replace used K slowly. Thus the release of K will be rapid and slow accordingly. It then implies that soils with high PBC will be able to maintain solution K intensity against plant depletion for longer periods of time while those of low values will have a low capacity to maintain the activity ratio and hence frequent fertilization. Observations on the change in free energy of exchange (ΔG) indicate that 80% of the farm soils and 67% of the greenhouse soils were K sufficient. This observation agrees with the findings of Roy et al. (1991); Evangelou et al. (1994); Jalali (2007). They reported that soils with ΔG greater than 3,500 kcal for the replacement of Ca and Mg with K are K deficient. They however, reported that soils ideal in this respect should fall in a range of 2,500–3,000 Kcal. Soil that have a ΔG less or equal to 2,000 Kcal is associated with Ca deficiency created by the excess amount of K. The ΔG value observed in these soils could be due to their magnitude of exchange capacities and retention of K on the exchange complex. Response to K fertilization varied among the 12 soils. It was however, observed that soils low in available K responded more to K fertilization, this is also reflected in the dry matter yield, and K concentration in the soybean crop.

Correlation and regression among soil and agronomic parameters

The correlation analyses showed that solution K is the most consistent determinant of the soybean dry matter yield and K concentration in the plant. The solution K was still strongly correlated with soybean dry matter yield even at the 4th harvest. The soil available K, exchangeable K and solution K also describes the K concentration in soybean up to the 5th harvest. Similar results were observed by Adetunji and Adepetu (1993), on some Nigerian soils. The Regression analyses show that more than 60% of the labile K is determined by the amount of clay in the soil, variability in clay mineralogy has been reported as a major determinant of K chemistry in the soil (Officer et al. 2006; Jalali 2007; Schindler et al. 2005). The equilibrium activity ratio can also be 76 and 99% predicted by the clay content and ECEC, respectively. About 66% variation in PBC of the soils is also determined by the soil clay content. This may be due to the relatively high variation in chemical and physical properties of the studied soils. Jalali (2007) reported a positive relationship between PBC and clay content of some Iranian soils. For the field soils, all the K forms were strongly correlated with soybean grain yield, however, soil available K, exchangeable K + fixed K, solution K + fixed K, and specifically bonded K appeared as the major contributor. These correlations were in accordance with the findings of Datta and Sastry (1993).

Critical level of K forms

The implication of the critical values is that the soil will need K fertilization when the analytical values of soil K are below 0.35 cmol kg^{-1} for available K, 0.21 cmol kg^{-1} for labile K and 0.19 cmol kg^{-1} for specifically-bonded K. The slight variation in these values might be due to the ease to which plant access the available K portion while others were only used when the solution and available K are exhausted. Using these values, about eight of the soils are deficient in available K, six soils deficient in labile K while only eight soils were deficient in specifically bonded K. This perhaps explains the reason for the positive responses observed with the application of K fertilizers in these soils. It also means that with soil available K of 0.35 cmol kg^{-1}, analytical values lesser than this indicates that there is likely to be a positive response to K fertilization in the soil. However, if higher, there is no guarantee of economic response to the applied K fertilizers, same for other critical values gotten. Plants will experience K deficiency symptoms if labile K is depleted below 0.21 cmol kg^{-1} and specifically bounded K below 0.19 cmol kg^{-1}. Particularly, if the K forms are not replenished quickly enough. Schindler et al. (2005). However, when soils similar to those studied are at the critical values of the K forms determined, slight differences in the soil's chemical and physical properties may significantly affect K release to soil solution.

Conclusions

The results show that about 20% of the field soils and 33% of the greenhouse soils studied were K deficient, thus explaining the responses to K fertilization observed in the study. About 50% of the soils in the greenhouse and in the farmers' field have high buffering capacity, indicating that depletion of K on cropping will be slower in these soils. The clay content of the soil is a major determinant of the amount of labile K, activity ratio and the buffering capacity of the soils. The external (soil) critical level of K for soybean production was estimated as 0.35, 0.21, and 0.19 cmol kg^{-1} for available K, labile K and specifically-bonded K, respectively.

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