POTASSIUM STUDIES ON AN AVALON MEDIUM SANDY LOAM

by

MARTIN PATRICK WARNER FARIÑA

B.Sc. (AGRIC.) NATAL. M.Sc. (AGRIC.) NATAL.

Submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy in the Department of Crop Science, Faculty of Agriculture, University of Natal

Pietermaritzburg 1970

C O N T E N T S

ABSTRACT

Chapter 1 The Avalon medium sandy loam

The Avalon medium sandy loam is considered to be one of Natal's most important agricultural soils and together with closely related sandy variants of the Avalon soil form covers some 200,000 hectares of the Tugela Basin. Selected physical and chemical characteristics of the particular soil, which provided the basis for the studies discussed in this dissertation, were presented.

Chapter 2 Effects of rainfall and differential applications of N, P, K, and Ca on the fate of K in an Avalon medium sandy loam cropped with maize (Zea mays L.)

Soil and plant samples were obtained from a field experiment in which different levels of N, P, K, and Ca were combined in a 3^4 factorial arrangement. The pattern of K movement in topsoil (0 - 15cm) was measured over a period of three years and related to rainfall and crop removal. The extent of K drainage to subsoil horizons over two seasons was determined and the effects of N, P, K, and Ca levels on K movement both to lower horizons and the growing plant assessed.

Marked luxury consumption and leaching from the surface horizon occurred. The extent of K loss to subsoil horizons was largely dependent upon rainfall and rate of K application and was unaffected by the addition of other fertilizers. Textural build-up prevented movement of K beyond the 45 - 60cm zone. Although N and P had no direct effect on K movement to lower horizons, such losses were appreciably reduced by increases in plant uptake at high rates of N and P fertilization. Applications of Ca did not affect plant uptake of K, but increased levels of K resulted in reduced uptake of both Ca and Mg. Losses of K from aerial plant parts during senescence were considerable.

Chapter 3 *A field and glasshouse comparison of several potassium availability indices*

Data from both field and pot studies were used to compare and evaluate several K availability indices.

In a pot study with *Eragrostis curvula* indices of K availability obtained by exchange with neutral N NH_4OAc and the quantity-intensity (Q/I) technique were correlated with cumulative yield, cumulative K uptake, and K% in the tissue. All the parameters used provided essentially similar indices of K availability when soil was not dried prior to analysis. Air drying, however, markedly reduced the prognostic value of N NH_4OAc exchangeable K and K index A, the product of labile pool ($-\Delta K^o$) and potential buffering capacity (PBC^K).

In a field study with maize (*Zea mays* L.) the various indices of K availability were correlated with K% in the stover at four stages during the growing season. Although all soil analyses were conducted on air dry samples, N NH_4OAc exchangeable K provided as good an index of K availability as any of the other measures used and proved superior to equilibrium activity ratio (AR_o^K) or parameters involving PBC^K measurements.

Data from both the field and pot studies suggested that the form of the Q/I relationship was affected by air drying and K fertilization.

Chapter 4 *Potassium availability in the profile of an Avalon medium sandy loam as measured by several soil test methods and exhaustive cropping in pots*

K availability indices obtained by empirical methods using N NH_4OAc at pH 7, 0.01 M $CaCl_2$, 0.001 M $CaCl_2$, and N HNO_3 were compared with indices obtained from techniques involving intensity measurements in six horizons of an Avalon medium sandy loam. *Lolium perene* (cv

$\underline{N}$ NH_4OAc exchangeable K provided an index of K availability superior to those obtained by other methods. Apart from being a good index of K availability $\underline{N}$ NH_4OAc exchangeable K was closely related quantitatively to cumulative uptake by the time deficiency symptoms first appeared. Labile pool ($-\Delta K^o$), equilibrium activity ratio (AR_o^K), and the energy of exchange of Ca by K (ΔF) were poorly correlated with uptake. Joint consideration of Q/I parameters, however, provided greatly improved measures of K availability. $CaCl_2$ equilibrations provided only reasonable indices of K availability, the prognostic values of which tended to decrease as the soils were exhausted. While $\underline{N}$ HNO_3 releasable K was initially poorly related to uptake, it provided an improved index as K depletion progressed and initially nonexchangeable K played an increasingly important rôle.

Chapter 5 – <u>Effects of K release and fixation on the quantity-intensity relations of an Avalon medium sandy loam</u>

To ascertain whether release and fixation phenomena significantly alter the Q/I relations of an Avalon medium sandy loam K equilibrium shifts were promoted by fertilizing with K, incubating for various periods at different moisture contents, and air drying prior to analysis.

Level of K application, time of incubation, and air drying were all found to significantly affect the form of the Q/I relationship. Applications of K resulted in decreases in PBC^K due apparently to blocking of exchange sites. Although small quantities of applied K were fixed, release of K occurred on storage and PBC^K values increased. Thus, the effects of K application on PBC^K tended to diminish with time of incubation. Changes in PBC^K per unit increment in K diminished as the level of K saturation increased and PBC^K increases per two week incubation period were similarly greater at higher levels of K. Air drying soil samples prior to analysis resulted in significant PBC^K increases. K release on drying presumably resulted in increases in cation exchange capacity and enhanced adsorption of Ca.

INTRODUCTION

It is axiomatic that any sound agricultural research programme should hinge ultimately upon the need to answer practical problems confronting the farming community. The nature and complexity of such problems varies tremendously being largely dependent upon the agricultural development of the country or area involved. In the agriculturally advanced regions of North America and Western Europe many of the more fundamental requirements have been fulfilled and much of the present research is of an advanced and complex nature. In younger underdeveloped and developing countries, however, considerable popularly called "bread and butter" research must still be undertaken. In the field of soils research South Africa's requirements and achievements probably fall somewhere between these two broad limits. In certain specialised directions they are equal to those of the most technically advanced nations, while in others they are as rudimentary as those of many far less developed countries. Field calibration studies and the establishment of threshold values for various crops and soil types, is one such neglected avenue of research. There is disturbingly little information available in this regard, notwithstanding the fact, that nearly 3,000,000 metric tons of fertilizer material are used each year. An annual investment by the farming community of over R87,000,000 should be backed by a sound soil testing service, yet there are very few areas in the country where fertilizer requirements are predictable with any degree of accuracy. Sound correlation studies must precede the intelligent interpretation of soil test values, but there exists at present a totally inadequate background in this regard and considerable research relating to soil fertility has consequently found little or no practical application. While the necessity for immediate returns from research does not exist in many agriculturally advanced countries, it is very doubtful whether South Africa can realistically afford such luxuries at present.

Of the numerous factors which have probably contributed towards

First, there has until recently, due to the absence of any detailed soil survey or classification system, been no satisfactory research vehicle on which to conduct calibration studies. A thorough survey of the Tugela Basin, an area of considerable agroeconomic potential, initiated in 1957 and published very recently (van der Eyk, MacVicar, and de Villiers, 1969) has, however, made a sound approach to this problem feasible. Secondly, there has in the past been insufficient co-operation between soil and crop scientists. In South Africa these two disciplines unfortunately tend to operate to the exclusion of one another and ground of common interest, such as crop nutrition and soil fertility, has consequently been rather neglected. This is exemplified by the very large number of fertility trials performed annually with no consideration of soil test values. In the absence of the extrapolatory value provided by such analytical data, results obtained from these experiments have not proved particularly meaningful in areas other than those in the immediate environs of the research centres involved. Last, a factor which has probably also contributed indirectly to this lack of co-operation. There is an apparent reluctance among research personnel to conduct what many feel is rather humdrum research. This is undoubtedly due largely to the modern tendency to guage proficiency on the complexity and volume of published work. In most respects South Africa is very closely linked to the further developed countries of the Western World and there is a tendency to favour research programmes abreast of those conducted in these countries, such work rightly or wrongly being considered better suited to publication. While this satisfies both national requirements and individual desires in many fields of endeavour where research findings have universal application e.g. heart surgery, it is not entirely possible in the field of soil fertility. Variables such as climate, topography and parent material, all intimately involved in soil genesis, as well as the wide divergence in crop requirements, preclude the satisfactory pooling of information from dissimilar areas for the prediction of fertility requirements. Indeed, it is questionable on a relatively localised scale, where the requirements of individual or at least closely related soil types are carefully studied.

It is not intended here to offer possible solutions to these problems, but merely to present them as being among those, which have had an important bearing on soil fertility studies in this country. Further, while it is not suggested that such difficulties are peculiar to South Africa, the situation existing in the country in general and in the province of Natal in particular was an important factor in the motivation of the studies reported here.

During 1965, when the Tugela Basin survey was approaching completion, it was decided to conduct calibration studies on the most important soil types occurring in this area. The Avalon medium sandy loam was selected as the most suitable soil type on which to initiate such studies as, apart from being well represented on a research station, it was considered to be agriculturally very closely related to the other infertile sandy soils of this area. Such soils constitute 15 - 20% of all arable land in the Tugela Basin and their low productivity has been held to be largely responsible for the economic depression existing in areas of their most frequent occurrence. Moreover, very similar sandy soils are known to occur extensively in other parts of Natal and the important cropping areas of the Transvaal and Orange Free State.

The work reported here is based on a long term fertility trial laid down in the spring of 1966 on the Dundee Research Station near Dundee, northern Natal. Although the ultimate objective of this experiment is the establishment of minimum soil test values for N, P, and K above which increases in maize yield will no longer be economic, this report is restricted to essential preliminary studies involving K. While the choice of K was influenced largely by the considerable volume of work into methods of K assessment conducted in Natal in recent years (Stanton, 1958; Le Roux, 1966; Koch, 1968; Skeen, 1968), sandy soils of the Avalon soil form are considered to be marginal with respect to K (van der Eyk <u>et al</u>., 1969) and the importation of K contributes significantly to South Africa's annual outlay of foreign exchange.*

The success of a calibration study is ultimately dependent upon the efficacy of the soil testing technique adopted. Without a thorough understanding of the significance of factors such as fixation, leaching, luxury consumption, and nutrient interaction to the particular soil-plant system under investigation, however, no soil test can be adequately interpreted. Thus, an evaluation of soil testing techniques and the establishment of basic soil-plant relationships involving the particular nutrient being studied must precede correlative work.

Overall objectives of the work reported here were to (1) investigate some of the basic soil-plant relationships which might play a rôle in the K nutrition of maize on Avalon medium sandy loams and (2) compare and evaluate a number of techniques used for determining plant available K.

---

* According to figures released by the Department of Agricultural Technical Services consumption during 1968 was equivalent to 79,764 metric tons of K.

CHAPTER 1

THE AVALON MEDIUM SANDY LOAM

Soils of the Avalon and Glencoe forms, as described by van der Eyk, MacVicar, and de Villiers (1969) are characterised by an orthic A horizon over a yellow apedal B horizon underlain by either soft (Avalon form) or consolidated (Glencoe form) plinthite (plates and tables 1 and 2).

Two or more members of these soil forms are regularly associated in the landscape and are dominant constituents of the five E mapping associations of van der Eyk et al., (1969). Landscapes in which members of the Leksand and Newcastle series predominate, but which contain extensive areas of Avalon series and occasional representatives of the Bleeksand and Ruston series have been grouped into the Leksand-Avalon (E3) mapping association. Similarly landscapes in which members of the Leksand, Wesselsnek and Dunbar series predominate, but which contain extensive areas of the Newcastle and Driepan series and occasional representative of the Glencoe and Avalon series have been grouped into the Leksand-Wesselsnek (E4) mapping association.

Soils of both these associations tend to be sandy and commonly have non-diagnostic A horizons which are indistinguishable. Indeed, the diagnostic B horizons of the sub-dominant series in both associations are frequently only distinguishable from the dominant series by recourse to particle size analysis. Consequently, except where consolidated plinthite imposes restrictions on rooting depth, soils in these two associations are considered to be agriculturally very similar. In practice no attempt is made at present to differentiate between soils included in the E3 and E4 associations and they are collectively referred to as "Leksands" by field officers. Although primarily to avoid unnecessary confusion among the farming community, this grouping is also considered to have merit as far as fertility studies are concerned. Fertilizer and management responses are likely to be sufficiently

Plate 1 Avalon soil form

Table 1 Soils of the Avalon form

Clay content of yellow B horizon (%)	Dominant grade of sand in yellow B horizon	S-value in yellow B horizon (me%)*	
		Below 1.5	1.5 - 5.0
6 - 15	coarse	Newcastle	
	medium	Leksand	
	fine	Bleeksand	
15 - 35		Ruston	Avalon
35		Normandien	Bergville

* Sum of metal cations

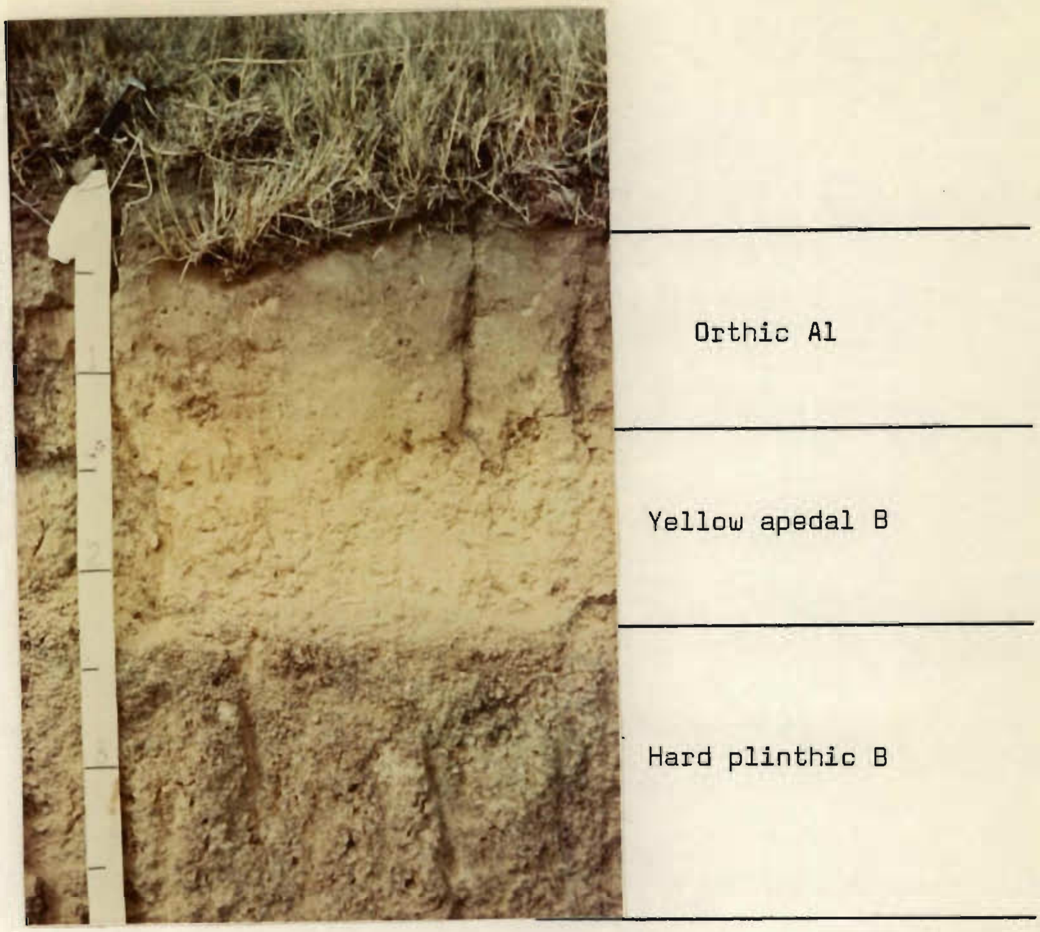


Plate 2 Glencoe soil form

Table 2 Soils of the Glencoe form

Clay content of yellow B horizon (%)	Dominant grade of sand in yellow B horizon	S-value in yellow B horizon (me%)*	
		below 1.5	1.5 - 5.0
6 - 15	coarse	Wesselsnek	
	medium	Dunbar	
	fine	Driepan	
15 - 35		Appam	Glencoe

* Sum of metal cations

similar to make sub-division unrealistic at this stage and it is expected that it will be possible to extrapolate experimental results obtained on an Avalon medium sandy loam to other members of the E3 and E4 associations, of similar effective depth, with considerable confidence. Approximately half of the 1,300,000 hectares of arable land in the Tugela Basin belongs to the E mapping association. Of this, 120,000 hectares belong to the E3 association and over 85,000 hectares to the E4 association. Consequently, it is anticipated that the Avalon medium sandy loam will be representative of almost 200,000 hectares in the Tugela Basin.

Sandy variants of the Avalon and closely related series occur largely in the northern portion of the Tugela Basin (fig. 1), an area subjected to climatic conditions generally very favourable for intensive cropping. Normal annual rainfall is adequate and summer temperatures are high.

These soils have developed on drift material originating from Karoo sandstone (Ecca) and are usually moderately deep to deep. They are in general moderately leached yellowish-brown to grey-brown in colour and most often free of ferruginous hardpans. The surface horizons have single grain or, at best, weakly developed structures and a very low organic matter content. Structure becomes stronger, consistence firmer and the clay content, pH and exchangeable cations increase with depth. Conspicuous red mottles appear in the lower horizons and hydromorphism becomes progressively more marked. The predominant clay minerals are kaolinite and illite with some muscovite.

Selected physical and chemical properties of a profile representative of the particular Avalon medium sandy loam used in these investigations (plate 3) are presented in table 3.

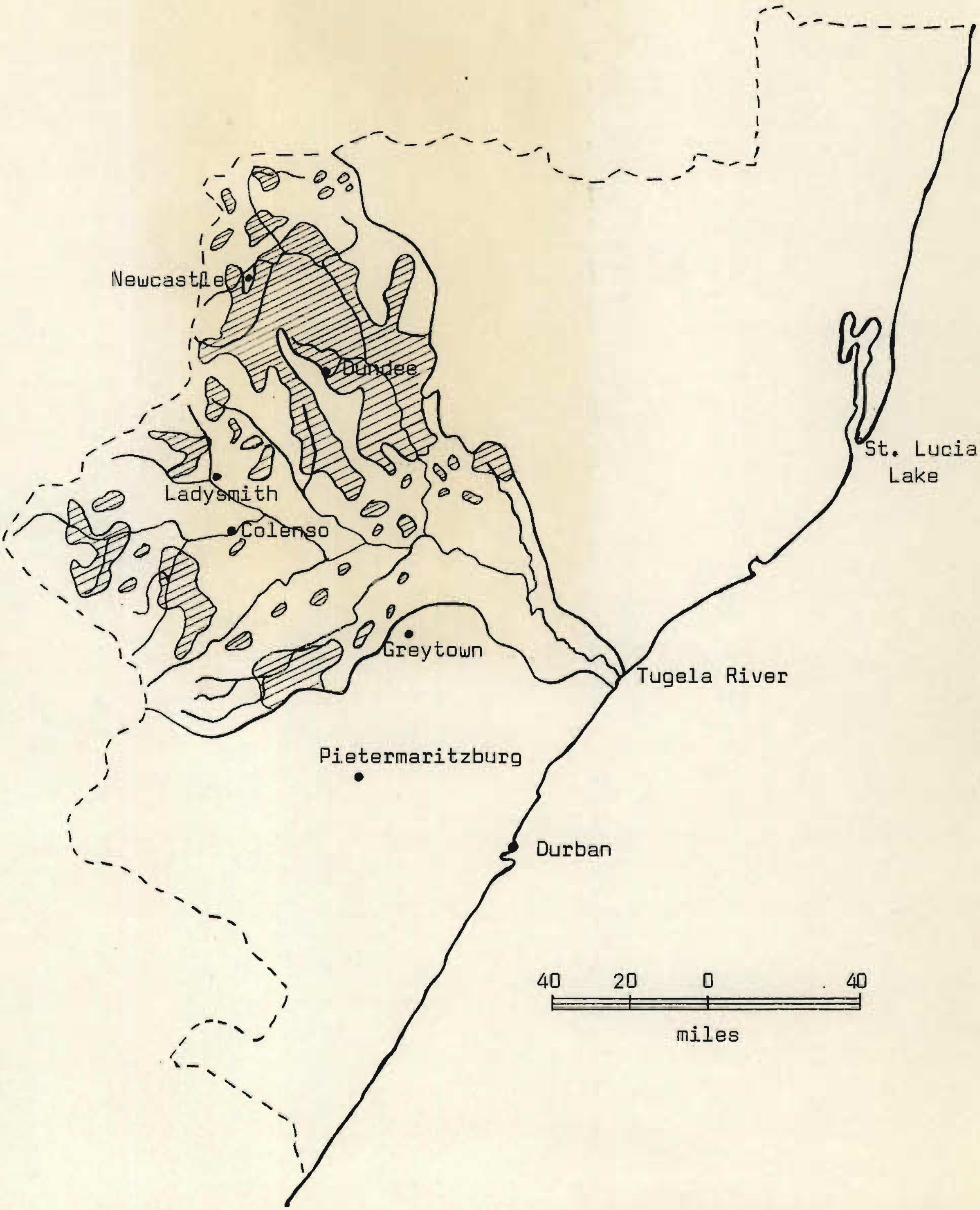
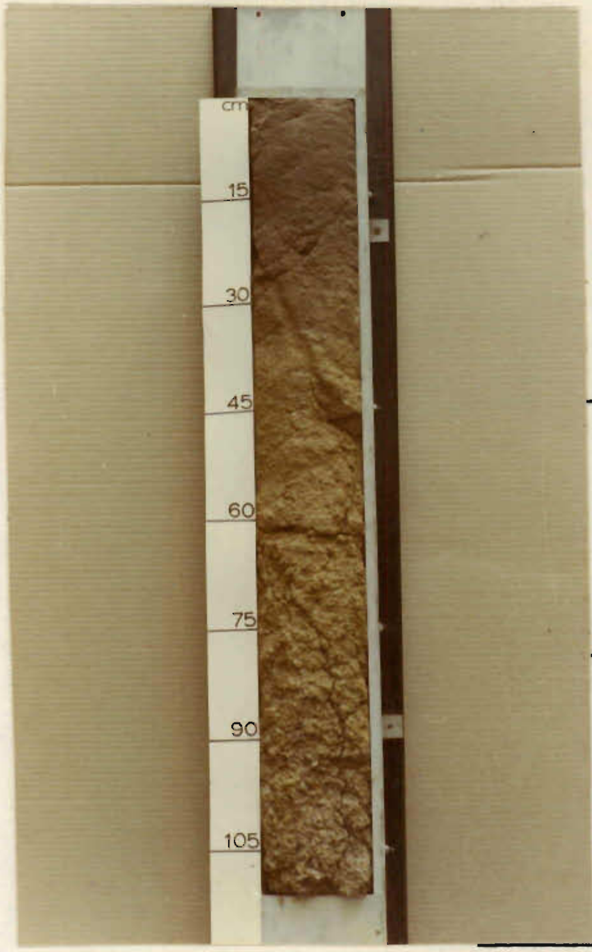


Fig. 1 Map of Natal showing distribution of E association soils



Orthic A1

Yellow apedal B

Soft plinthic B

Plate 3 Avalon medium sandy loam monolith

Table 3 Selected physical and chemical characteristics of six soil horizons of an Avalon medium sandy loam

	Horizon					
	0-15cm	15-30cm	30-45cm	45-60cm	60-75cm	75-90cm
	Particle size distribution % (Hydrometer)					
c. sand	12	12	12	9	7	6
m. sand	27	24	27	18	12	11
f. sand	43	45	31	33	30	28
silt	4	4	6	6	8	8
clay	14	15	24	34	42	46
	Extractable cations in me% ($\underline{N}$ NH_4OAc pH7)					
Na	.02	.02	.03	.12	.28	.34
K	.16	.15	.14	.12	.36	.58
Ca	.56	.63	.69	.69	.94	1.40
Mg	.22	.26	.81	1.87	4.19	4.56
* S value (me%)	.96	1.06	1.67	2.80	5.77	6.88
† C.E.C. (me%)	1.61	1.70	3.24	4.58	8.43	9.00
% base saturation	59.5	62.5	51.5	61.0	68.5	76.5
pH $\underline{N}$KCl (1:2)	3.9	3.9	3.9	4.0	4.5	4.9

CHAPTER 2

EFFECTS OF RAINFALL AND DIFFERENTIAL APPLICATIONS OF N, P, K, AND Ca ON THE FATE OF K IN AN AVALON MEDIUM SANDY LOAM CROPPED WITH MAIZE (*Zea mays* L.)

INTRODUCTION

In any fertility study pertaining to the rôle of K in a particular soil-plant system, information regarding the fate of applied K under field conditions is essential, as losses due to leaching and luxury consumption may be of considerable agronomic consequence.

In most agricultural soils vertical movement of applied K is limited (Duthion, 1968). In sandy soils, of which there are approximately 200,000 hectares in the Tugela Basin, however, leaching of potassic fertilizers is an important consideration (Mehlich and Reed, 1945; Pratt and Goulben, 1957; Jackson and Thomas, 1960; Luterick, 1963; Pfaff, 1963; Hogg and Cooper, 1964; Köhlein, Oehring, and Spielhaus, 1966). Intensity, duration, and frequency of rainfall are major contributory factors to K movement (Munson and Nelson, 1963). In addition, variable effects due to the application of other fertilizers have been reported (Ayers and Hagihara, 1953; Luterick, 1963; Hogg and Cooper, 1964; Paterson and Richer, 1966). A frequently overlooked factor of major importance in leaching studies is the growing plant. Plants must, depending on rooting habit and specific K requirement, reduce leaching losses both by interception and recycling of K from lower horizons. Consequently, other nutrients will, apart from any direct effect they may have in uncropped soil, influence leaching losses through their effects on plant growth.

The aim of this investigation was to determine what effects fertilization, cropping with maize and seasonal variation have on the fate of K applied to an Avalon medium sandy loam.

MATERIALS AND METHODS

experiment initiated in 1966 near Dundee, northern Natal. Selected physical and chemical properties of a representative profile have been presented earlier (table 3). Three levels of N, P, K, and Ca were applied annually in all combinations to eighty-one 0.0078 hectare plots arranged in a single replicate 3^4 design. The following fertilizers were used: urea (53.5, 107.0, 214.0 kg N/ha), single superphosphate (24.2, 48.4, 96.8 kg P/ha), muriate of potash (0, 87.3, 174.6 kg K/ha), and gypsum (0, 102, 204 kg Ca/ha). All fertilizer except two thirds of the urea, which was applied as a side-dressing when plants in the best plots were approximately 45cm high, was broadcast and disced into the soil just prior to planting. Uniform dressings of $ZnSO_4.7H_2O$ (26.5 kg/ha), $CuSo_4.5H_2O$ (26.5 kg/ha), Borax (26.5 kg/ha) and $(NH_4)_6Mo_7O_{24}.4H_2O$ (0.5 kg/ha) were applied at the start of the 1966/67 season. $MgSO_4.7H_2O$ (233 kg/ha) was applied annually. The yellow maize cultivar 'S.A. 60' was planted at a spacing of 30 x 90cm.

Prior to fertilization and at seven stages in the 1966/67 and six in the 1967/68 and 1968/69 seasons soil samples were collected from the surface 15cm of each plot using a Beater sampler. Thirty cores were removed per plot, ten each from between plants in the row, quarterway between the rows and midway between rows. At the beginning of the third season 15cm soil increments were collected to a depth of 60cm using a split-tube sampler. Nine cores were removed per plot.

Soil samples were air dried and ground to 2mm. Exchangeable K was extracted by shaking with neutral N NH_4OAc for 30 minutes using a 1:10 soil to solution ratio. To measure K release or fixation in the various soil horizons, nonexchangeable K was determined as the difference between exchangeable K and that extracted by boiling with N HNO_3 for 10 minutes using a soil to solution ratio of 1:5. Analyses were conducted in duplicate and K determined flame spectrophotometrically in filtered extracts.

Coincident with soil sampling, plant samples were collected at

165 days after planting) and at two stages during the 1967/68 season (28 and 170 days after planting). Five plants were removed from each plot, weighed and chaffed. An approximately 500g subsample was dried to constant weight at 90^{o}, weighed and milled. In the fifth, sixth, and seventh samplings cobs and stover were treated separately. K, Ca, and Mg were determined in filtered extracts after ashing 2g samples at 450^{o} and dissolution in 1+4 HCl. At harvest grain and stover yields were recorded and removed from the experimental site.

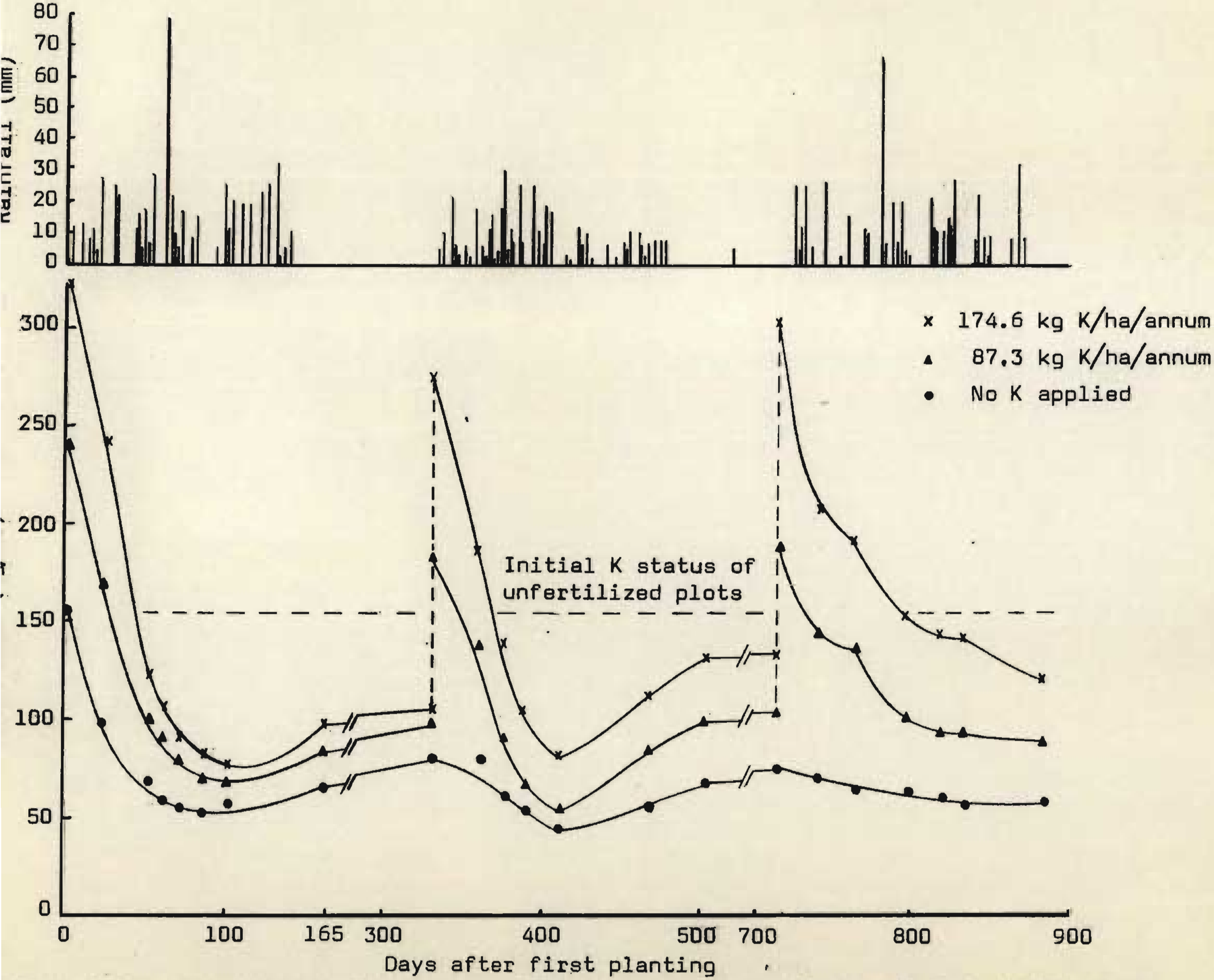
RESULTS AND DISCUSSION

(i) Pattern of K movement in topsoil

Figure 2 depicts the mean K status in topsoil (0-15cm) of the K_0, K_1, and K_2 plots over all levels of N, P, and Ca, together with the daily rainfall during three seasons of cropping with maize. It is apparent that (a) even at the highest level of application there was a net reduction in K status, (b) the percentage K loss increased with level of application, (c) considerable recovery of K occurred during the latter portion of the first two seasons, and (d) the pattern of K movement was influenced markedly by rainfall.

Plant analysis indicated that the net K loss from plots receiving annual K applications of 87.3 kg/ha (K_1) and 174.6 kg/ha (K_2) was considerably in excess of the K removed by the crop during the 1966/67 and 1967/68 seasons (table 4). As the surface horizon is not capable of fixing significant quantities of K (chapter 5), such losses were presumably due to movement down the profile. Failure of K dressings to maintain the original K status of the unfertilized soil was probably the result of other fertilizer materials increasing competition for exchange sites, since cropping did not bring about any reduction in the organic matter content.

Predictably, where a soil has little capacity for K retention, losses of K due to drainage increased markedly with level of application, leaching losses from K plots being almost three times those from K



ig. 2 Potassium status in the surface 15cm of an Avalon medium sandy loam during three seasons of cropping with maize. (Each point represents mean of 27 plot values.)

Table 4 The effects of annual precipitation and cropping with maize on K loss from the surface 15cm of an Avalon medium sandy loam

Season	Rainfall (mm)	K applied (kg/ha)	K removed by crop (kg/ha)	Reduction in soil K status (kg/ha)	K presumed leached to lower horizons (kg/ha)
1966/67	619	174.6	115.9	224.3	108.4
		87.3	103.7	145.5	41.8
		nil	93.6	73.0	
1967/68	427	174.6	66.1	145.0	78.8
		87.3	58.2	83.1	24.9
		nil	47.0	14.1	

were nonsignificant over the three seasons of experimentation (table 5), total K uptake in K_2 plots was 26% higher than that in K_0 plots during 1966/67 and 41% higher during 1967/68 (table 4).

Table 5 Effects of annual applications of N, P, K, and Ca on maize grain yields*

Annual treatment (kg/ha)		Season		
		1966/67	1967/68	1968/69
53.5	N as urea	3804	3700	3657
107.0		5156	4472	4047
214.0		5966	4293	3060
24.2	P as single superphosphate	3739	3890	3348
48.4		5020	4056	3476
96.8		6164	4519	3941
0	K as muriate of potash	4970	4022	3403
87.3		4966	4230	3698
174.6		4988	4211	3662
0	Ca as gypsum	4992	4211	3498
102		4995	4042	3595
204		4936	4212	3672
Mean yield		4975	4155	3587
SE		137	123	118
LSD 5%		392	352	337
1%		524	470	451

In the first two seasons losses of K from aerial plant parts 90-100 days after planting until harvest resulted in a rapid build-up in soil K status (figs. 2 and 3a). During 1966/67 apparent K loss varied from 8% (K_0) to 20% (K_2) of maximum plant content (fig. 3a). This is considerably higher than losses reported by Hanway (1962), Sayre (1955), and Weinmann (1956) and was probably due largely to plants attaining a higher maximum K content. Factors such as degree of senescence at harvesting, rainfall, and variety play a rôle, however (Tuckey and Tuckey, 1962; Mecklenburg, Tuckey and Morgan, 1966).

Results also suggest that apparent plant loss may be appreciably less than actual loss. Increases in the K status of K_2 plots during the 1966/67 and 1967/68 seasons amounted respectively to 31 kg/ha and 47 kg/ha (fig. 2). Insufficient plant samples were collected during the 1967/68 season to determine plant loss directly, but it is considered unlikely that soil gains would have been greater than during the 1966/67 season, as mean yields were 21% lower (table 5). It appears rather that higher rainfall during the 1966/67 season resulted in apparent soil gains being substantially less than actual gains, plant K being leached to subsurface horizons. As increase in soil K during the first season (fig. 2) was very similar to decrease in plant K (fig. 3a), apparent plant losses also appear to have been lower than actual losses. This is not inconsistent with findings reported in the literature. Tuckey and Tuckey (1959; 1962) have demonstrated with the use of radioactive isotopes that leached K may be recycled. In the work reported here influx of K probably continued for some time after plants suffered a net decrease in K content. This would explain why Hanway (1962) observed K accumulation in maize until a considerably later stage of maturity than Sayre (1955). Leaching losses reported by Sayre were in the region of 12%, whereas those measured by Hanway were negligible.

Terminal decrease in soil K status recorded during the 1968/69 season (fig. 2) supports the contention that, due to the higher

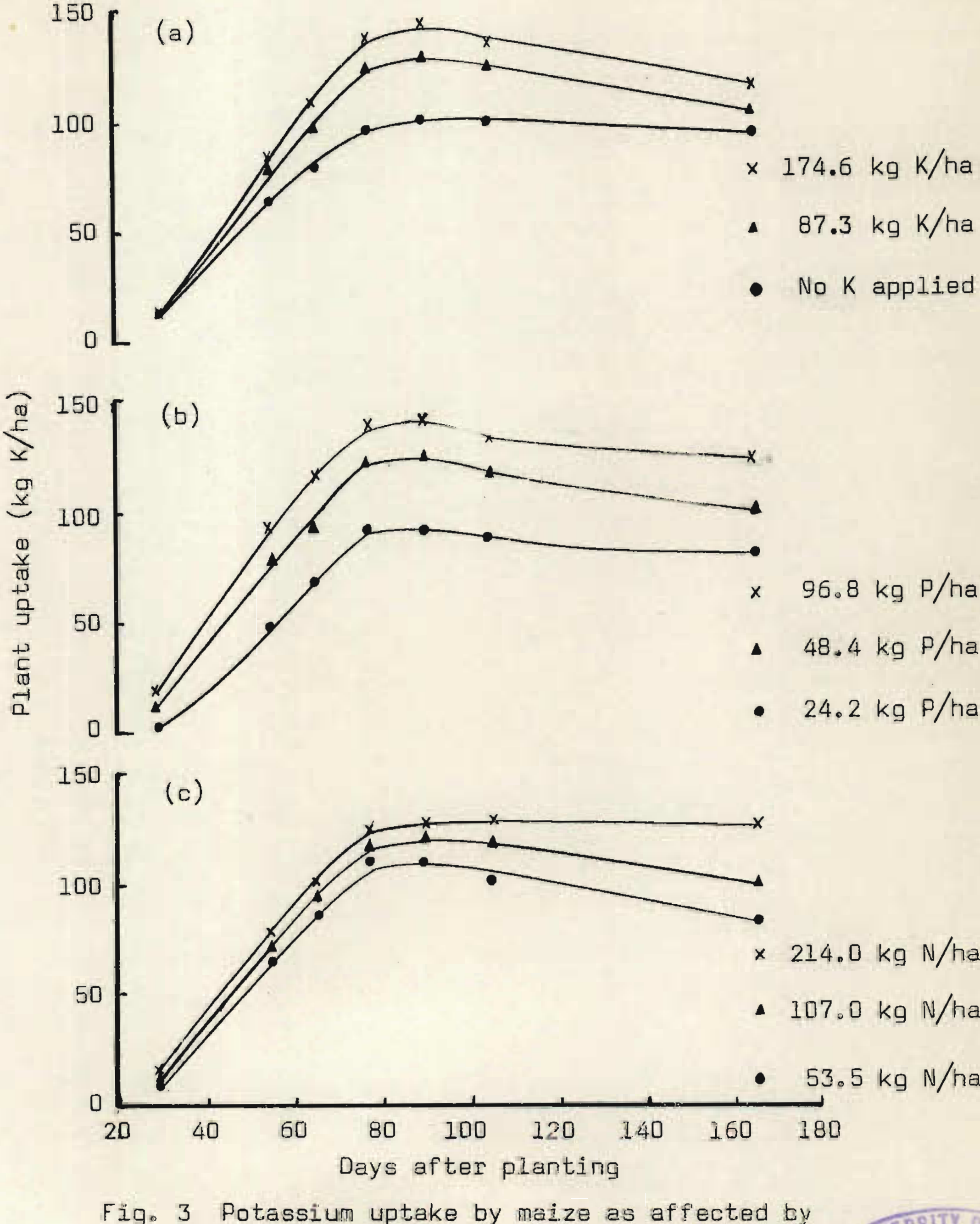


Fig. 3 Potassium uptake by maize as affected by (a) level of K, (b) level of P, and (c) level of N. (Each point represents mean of 27 plot values.)

physiological maturity, which occurred at an appreciably higher soil K status than in previous years due to the effects of drought, a marked decrease in K status was observed. This is considered to have been the result of relatively high intensity rainfall causing leaching losses from the soil to exceed gains from plant sources. As considerably more rain fell during the same period in 1966/67 a similar situation is likely to have existed, an increase in K status of the surface horizon resulting from substantially greater plant loss and the soils more advanced state of depletion.

While these data indicate that retention of applied K by the surface horizon is extremely tenuous, the agronomic consequences are dependent to a large extent on the depth to which K is leached.

(ii) K movement to lower horizons

Analyses of soil samples collected down the profile at the beginning of the third season indicated that, in plots receiving 174.6 kg K/ha annually, significant K movement had occurred to the 30-45cm horizon (fig. 4). If it is assumed that rooting depth was unaffected by K applications, significant K movement to the 30-45cm zone can also be regarded as having occurred in plots receiving 87.3 kg K/ha. In the 45-60cm horizon, although differences were not statistically significant, the same trend existed.

A considerable portion of the applied K could not be accounted for either in stover and grain removed or in the soil profile (table 6).

Table 6 Balance sheet showing the fate of K in an Avalon medium sandy loam cropped with maize for two years

K applied over two years (kg/ha)	K removed by maize (kg/ha)	K lost or gained by four depth increments (kg/ha)				Total K loss from profile	K not accounted for (kg/ha)
		0-15cm	15-30cm	30-45cm	45-60cm		
nil	140.6	- 87.1	- 15.9	- 5.3	- 5.3	113.6	-27.0
174.6	161.9	-228.6	+ 5.3	+10.6	+ 5.3	207.4	+45.5
349.2	182.0	-369.3	+ 42.3	+34.4	+13.2	279.4	+97.4

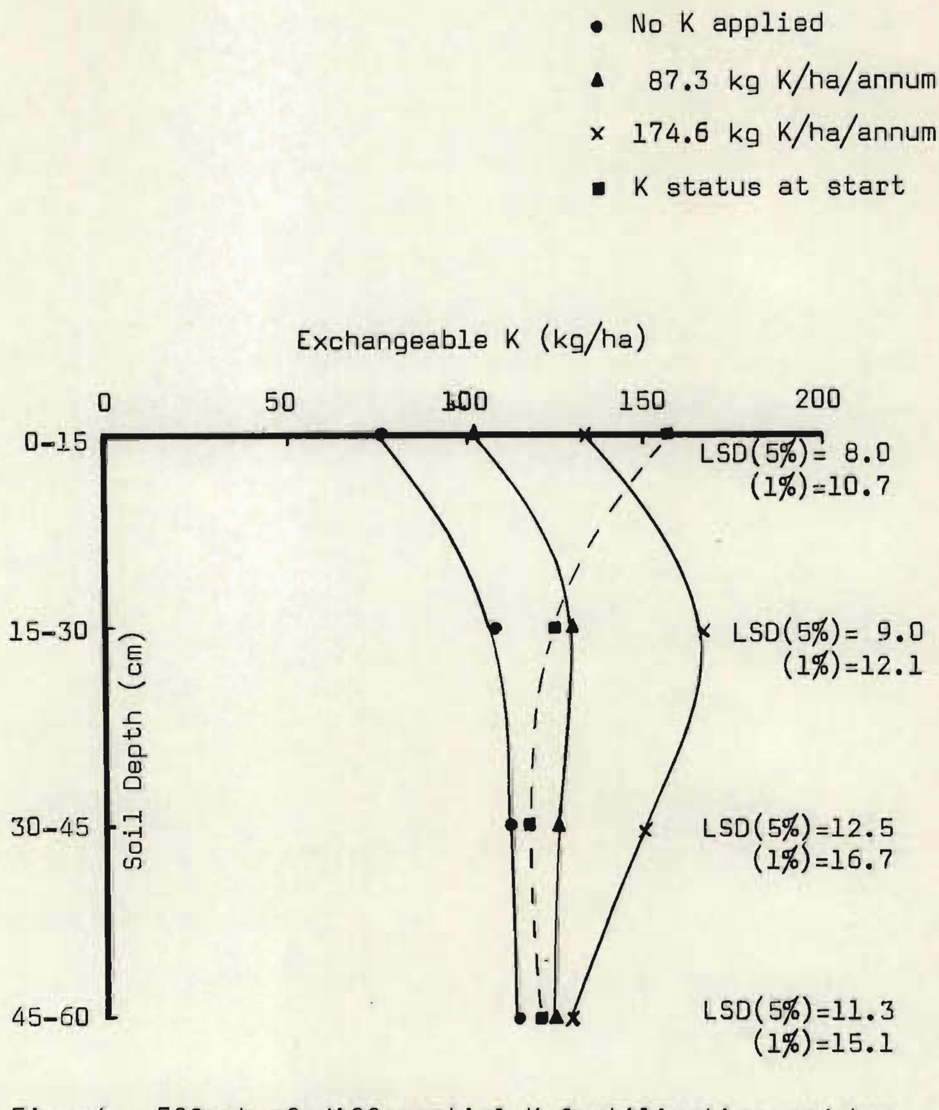


Fig. 4 Effect of differential K fertilization and two years of cropping on the K status in four horizons of an Avalon medium sandy loam. (Each point represents mean of 27 pot values.)

While some K was probably present in undecomposed crop residues, it is considered likely that fixation by subsurface horizons was largely responsible for the discrepancy. Although statistically significant differences in the level of nonexchangeable K could not be detected, such increases would be small and probably within the limits of experimental error when spread over two or more 15cm horizons. The apparent excess of K removed over K initially available in K_0 plots was presumably due to release from nonexchangeable sources throughout the profile and possibly removal from the K enriched hydromorphic zone below 60cm (table 3). Other work (chapter 4) has shown that, although the surface horizon is not capable of releasing meaningful quantities of K, such release increases down the profile. It is noteworthy that, notwithstanding very rapid loss of K from the surface horizon, applied K did not move beyond the rooting zone of most field crops.

(iii) Effects of N, P, and Ca on K movement down the profile

Ca in excess of the quantity present in the lowest superphosphate applications had no detectable effect on soil K status. Applications of N and P, on the other hand, resulted in highly significant ($P = 0.01$) decreases in the level of exchangeable K, N in the topsoil (0-15cm) and P to a depth of 30cm (table 7). These K losses did not

Table 7 Effects of N and P applications on the K status of four horizons of an Avalon medium sandy loam cropped with maize for two years

Annual application (kg/ha)		K status of soil horizons (kg/ha)			
		0-15cm	15-30cm	30-45cm	45-60cm
53.5	N as urea	118	151	137	131
107.0		113	145	135	125
214.0		106	143	140	135
24.2	P as single super-phosphate	120	153	142	133
48.4		111	154	137	127
96.8		106	132	133	131
SE		2.80	3.16	4.36	3.94
LSD 5%		8.0	9.0	12.5	11.3

lead to any concomitant increase in the K status of lower horizons, however, and were due solely to the beneficial effects of N and P on plant growth and K uptake. Low cation exchange capacity and relatively high base saturation of the surface horizons (0-30cm) probably account for the absence of the direct effects of gypsum and superphosphate reported by Mehlich and Reed (1954), Hogg and Cooper (1964), and others.

(iv) Effects of N, P, and Ca on K uptake

Applications of N and P resulted in marked increases in total K uptake and yield (table 5, figs. 3b and 3c). Increased K uptake was not directly proportional to growth, however.

High levels of N resulted in significant (P = 0.01) decreases in K% in plant material collected 29, 55, and 65 days after planting (table 8). Differences in K content were nonsignificant in subsequent

Table 8 Effects of N, P, K, and Ca applications on the K content of maize stover at seven stages during the growing season*

Treatment (kg/ha)		Days after planting						
		29	55	65	77	90	105	165
53.5	N as urea	4.60	3.92	2.82	1.98	1.55	1.40	1.40
107.0		4.39	3.70	2.67	1.95	1.52	1.53	1.39
214.0		4.30	3.42	2.52	1.92	1.53	1.51	1.47
24.2	P as single superphosphate	4.13	3.74	2.70	1.92	1.52	1.48	1.45
48.4		4.50	3.70	2.63	1.94	1.54	1.49	1.38
96.8		4.65	3.59	2.68	1.99	1.54	1.46	1.43
0	K as muriate of potash	3.90	2.91	2.13	1.62	1.28	1.32	1.28
87.3		4.65	3.83	2.69	1.98	1.54	1.45	1.38
174.6		4.73	4.30	3.19	2.24	1.79	1.66	1.60
0	Ca as gypsum	4.46	3.73	2.63	1.91	1.54	1.48	1.38
102		4.47	3.60	2.65	1.97	1.51	1.45	1.44
204		4.36	3.70	2.72	1.97	1.56	1.50	1.44
	SE	0.0543	0.0719	0.0385	0.0367	0.0235	0.0354	0.0363
	LSD 5%	0.155	0.205	0.110	0.105	0.067	0.101	0.104
	1%	0.208	0.275	0.147	0.140	0.090	0.136	0.139

samplings, but K loss by harvest was lower in high N plots. It appears that decreases in K content due to high levels of N were offset, as plants matured, by reduced leaching losses (fig. 3c). While decreases in K% due to high levels of N were undoubtedly due partly to dilution effects, decreases in the K/Ca and K/Mg ratios indicated that other mechanisms were operative (table 9). Such increases in the uptake of

Table 9 Influence of N rate on cation relations in maize stover at seven stages during the growing season

Days after planting	N added as urea (kg/ha)	N/K (%)	Cations (me%) K	Ca	Mg	K/Ca	K/Mg	Ca+Mg / K
29	53.5	0.63	117.7	16.7	24.2	7.1	4.9	0.35
	107.0	0.70	112.3	16.1	24.8	7.0	4.5	0.36
	214.0	0.83	110.0	14.9	23.6	7.4	4.7	0.35
55	53.5	0.64	100.3	13.1	17.2	7.7	5.8	0.30
	107.0	0.71	94.7	12.4	18.0	7.8	5.3	0.32
	214.0	0.83	87.5	12.3	17.9	7.2	4.9	0.35
65	53.5	0.65	72.1	10.4	16.3	7.3	4.4	0.37
	107.0	0.76	68.3	10.7	16.8	6.4	4.1	0.40
	214.0	0.91	64.5	10.6	16.8	6.2	3.9	0.42
77	53.5	0.73	50.7	8.7	12.2	5.8	4.2	0.41
	107.0	0.87	49.9	8.9	13.2	5.6	3.8	0.44
	214.0	1.00	49.1	9.6	13.5	5.2	3.6	0.47
90	53.5	0.65	39.7	8.6	10.8	4.6	3.7	0.49
	107.0	0.86	38.9	9.3	11.7	4.2	3.3	0.54
	214.0	1.05	39.1	9.7	12.1	4.0	3.2	0.56
105	53.5	0.39	35.8	9.9	11.2	3.6	3.2	0.59
	107.0	0.46	39.1	11.4	12.7	3.4	3.1	0.62
	214.0	0.64	38.6	12.5	12.3	3.1	3.1	0.64
165	53.5	0.34	35.8	9.0	12.0	4.0	3.0	0.59
	107.0	0.40	35.6	9.4	12.5	3.8	2.8	0.62
	214.0	0.47	37.6	10.2	12.4	3.7	3.0	0.60

Ca and Mg relative to K could have resulted from competition between NH_4^+ and K^+ ions (Boawn et al., 1960; Jakobsen, 1966; Kirby and Mengel and Franklin, 1956; McLean, 1957; Drake and White, 1961; Franklin, 1966).

Reduced K losses from plants receiving high levels of N were very probably due to the beneficial effects of N on longevity. Plants in high N plots had several green and apparently functional leaves at harvest, whereas those in low N plots were almost completely senesced. Physiological age of leaves is a major factor determining the degree of leaching (Tuckey and Tuckey, 1962) and this may partially explain the negligible K loss observed by Hanway (1962).

Superphosphate applications induced very significant ($P = 0.01$) increases in the K content of samples collected 29 days after planting (table 8). Any effects due to P were not apparent at later samplings, however, and the increased rate of K uptake is considered to have been due largely to the beneficial effects of P on establishment. Due to initial very rapid vertical movement of applied K, appreciably less K was probably available to poorly developed plants during the early stages of development.

Gypsum applications had no effect on the uptake of K. It is noteworthy, however, that K fertilization significantly decreased uptake of both Ca and Mg (table 10). Similar findings have frequently been reported and offer one of the major objections to the use of activity ratios in assessing K availability (Barber, 1968).

Table 10 Influence of K rate on Ca and Mg content of maize stover at seven stages during the growing season*

Days after planting	K applied (kg/ha)	Percentage Ca		Percentage Mg	
29	0	0.35	SE = 0.0059	.33	SE = 0.0076
	87.3	0.31	LSD = 0.017(5%)	.30	LSD = 0.022(5%)
	174.6	0.29	= 0.023(1%)	.25	= 0.029(1%)
55	0	0.27	SE = 0.0046	.25	SE = 0.0067
	87.3	0.26	LSD = 0.013(5%)	.22	LSD = 0.019(5%)
	174.6	0.23	= 0.018(1%)	.18	= 0.026(1%)
65	0	0.23	SE = 0.0052	.23	SE = 0.0052
	87.3	0.21	LSD = 0.015(5%)	.20	LSD = 0.015(5%)
	174.6	0.20	= 0.020(1%)	.18	= 0.020(1%)
77	0	0.18		.18	SE = 0.0037
	87.3	0.19		.16	LSD = 0.011(5%)
	174.6	0.18		.14	= 0.014(1%)
90	0	0.19		.16	SE = 0.0043
	87.3	0.19		.14	LSD = 0.012(5%)
	174.6	0.17		.12	= 0.016(1%)
105	0	0.23		.16	SE = 0.0032
	87.3	0.23		.15	LSD = 0.009(5%)
	174.6	0.21		.13	= 0.012(1%)
165	0	0.19		.17	SE = 0.0046
	87.3	0.19		.15	LSD = 0.013(5%)
	174.6	0.19		.13	= 0.018(1%)

* Ca and Mg expressed as percent of oven dry material

CONCLUSIONS

On sandy variants of the Avalon soil series the problem of K leaching does not appear to be so much one of losing K to zones beyond rooting depth, but rather of maintaining a sufficiently high K status in the topsoil during early growth. In the 1967/68 and 1968/69 seasons maize exhibited a marked yield response to K one month after planting

Topsoils of sandy Avalons are prone to dry out very rapidly and poor stands of maize frequently result from short periods of drought during early growth. It is consequently important that optimum seedling growth is ensured and small "starter" applications of K are likely to prove beneficial even where total K in the profile is considered adequate. Such "starter" applications will probably prove especially beneficial where smaller seeded crops, which are generally slower to become established, are grown. While spring ploughing and application of K as close as possible to the planting date is likely to ensure satisfactory early growth of crops such as maize, optimum establishment of pastures may require initial K dressings to be split.

The sequence of leachability of various sources of K is $KCl = KNO_3 > K_2SO_4 > K_2HPO_4 > K_3PO_4 = KPO_3 > K_2CaP_2O_7$ (Munson and Nelson, 1963). In South Africa K requirements are almost exclusively supplied as the chloride, nitrate and sulphate salts and use of less readily leached compounds may be warranted on certain soils.

The results presented clearly demonstrate the marked effects of N and P on K uptake. The rooting depth of maize, which may be increased by as much as 50% by proper fertilization (Munson and Nelson, 1963) exceeds 100cm in sandy loams (Fehrenbacher and Rust, 1956) and recovery of K from subsoil horizons was enhanced by both N and P dressings.

Marked luxury consumption, also evident in other work with subsoil horizons (chapter 4), suggests attempts to build up substantial K reserves in the rooting zone will be uneconomic. Rather, there should be a careful apportioning of K dressings to the crop needs for that year. Perennial pasture crops such as *Eragrostis curvula*, which is grown extensively in northern Natal and which may be cut four or five times during a single season, will probably benefit from splitting the annual K requirement into two or more top-dressings.

Rapid loss of K from the topsoil, significant leaching losses from aerial plant parts and the effects of N on both longevity and the uptake of K relative to Ca and Mg are likely to affect the usefulness of both soil and foliar analyses. Sampling to depths of 45cm is sufficiently such samples will provide a more meaningful index of plant available K than the 15cm soil cores presently used. Commercial concerns in South Africa are devoting considerable attention to foliar analysis as an aid in predicting the nutritional requirements of maize. The effects of leaching and N on leaching and the K/Ca and K/Mg ratios will clearly have to be considered. Time of sampling will be vital and increased uptake of Ca and Mg relative to K at high levels of N could possibly cause a shift in the critical K requirement.

CHAPTER 3

A FIELD AND GLASSHOUSE EVALUATION OF SEVERAL POTASSIUM AVAILABILITY INDICES

INTRODUCTION

It has long been a source of concern to soil scientists that the results of empirical extraction techniques, such as those proposed by Morgan, Bray, Dyer, and Truog, have only local significance. In recent years considerable attention has been devoted to devising soil test methods capable of more general application. Development and utilization of the concept of nutrient potential (Barrow, Ozanne, and Shaw, 1965) is considered to be a promising avenue of investigation.

Movement of any ion from the exchange complex is dependent, not on the absolute activity in solution phase of the particular ion, but rather on the ratio of the activities of all the ions concered (Boyed, Shubert, and Adamson, 1947). Schofield (1955) and Woodruff (1955) independently proposed that a soils ability to supply K to plant roots was measureable in terms of the activity ratio $^{a}K/\sqrt{^{a}Ca + ^{a}Mg}$, Ca and Mg being dominant cations in most agricultural soils.

Several workers have subsequently reported on the usefulness of activity ratio or intensity as a measure of plant available K. Some have reported favourably (Woodruff and McIntosh, 1960; Arnold, 1962a; Hagin and Dovrat, 1963; Moss, 1964; Ramamoorthy and Paliwal, 1962, 1965; Feigenbaum and Hagin, 1967; Koch, 1968), and others unfavourably (MacLean, 1960; Laws, 1962; Conyers, 1966; Conyers and McLean, 1969). Confounding of intensity and K level in the soil makes it difficult to determine a cause and effect relationship in experiments purporting to provide evidence for this belief, however (Barber, 1968). Furthermore, initial intensity measurements give little information about the continued capacity of a soil to supply K (Arnold, 1962b).

Beckett (1964a,b) developed a procedure for determining the maintain its original quantity and intensity values against depletion by cropping. It is presently popular to consider the availability of ions to plants as being a function of either labile pool or intensity measurements and the soils capacity to maintain these values against depletion. Application of the quantity-intensity (Q/I) concept, sometimes with minor variations has not, however, yet lead to any marked improvement in the diagnosis of soil fertility (Barrow, 1966; Zandstra and MacKenzie, 1968).

While it seems clear that any accurate assessment of K availability will indeed comprise an estimate of both the instantaneous supply and the soil's ability to maintain this supply from initially nonexchangeable sources (Duthion, 1968), there is reason to question the ability of the Q/I approach to adequately measure these parameters. Much publicity has been given to the advantages of using a technique based on sound thermodynamic principles, but the ultimate dependence of ion accumulation by plants upon metabolic processes has been largely ignored. There is, in fact, considerable evidence to indicate that the ratio $^{a}K/\sqrt{^{a}Ca + {}^{a}Mg}$ does not necessarily determine rate of K uptake (Collander, 1941; Peech and Bradfield, 1943; Viets, 1944; van Itallie, 1938, 1948; Jacobson and Handley, 1952; Bradfield and Peech, 1953; Overstreet and Jacobson, 1954; Waisel, 1962; see also page 27). Furthermore, rapid K uptake may continue after labile pool and intensity parameters determined in Q/I analysis have been reduced to zero (Le Roux and Sumner, 1968). Also, although labile pool values determined by Q/I analysis are generally appreciably lower than pool values determined by $\underline{N}$ NH_4OAc exchange, in many soils the fraction of soil K only removed by strong extractants, such as $\underline{N}$ HNO_3, must be considered (Fraps, 1929; Pratt, 1951; Acquaye, MacLean, and Rice, 1967).

Both fixation (Wood and De Turk, 1942; Attoe and Truog, 1946; Vasco da Gama, 1964) and release (Brown and Holmes, 1951; Leubs, Stanford, and Scott, 1956) of K may occur on air drying and the use of moist samples has been described as "one of the greatest breakthroughs in soil testing in recent years" (Nelson, 1967). Nevertheless, most samples. As the Q/I technique and neutral N NH_4OAc exchange do not measure the same fraction of soil K, pool values determined by the respective techniques are possibly not affected similarly by release/fixation phenomena.

The main purpose of this work was to compare, using moist and air dry samples, indices of K availability provided by N NH_4OAc exchange with indices obtained by techniques involving activity measurements and to establish the most suitable soil test method for determining plant available K on sandy soils of the Avalon type.

MATERIALS AND METHODS

Topsoil (0 - 15cm) of an Avalon medium sandy loam was used in both the glasshouse and field phases of this work. Selected physical and chemical properties of a representative profile have been presented elsewhere (table 3). Due to the practical difficulties involved in exhaustive cropping with maize, the crop used in field work, *Eragrostis curvula* (cv. Ermelo) was used in the pot study.

POT STUDY

Soil was collected from a site adjacent to the maize experiment, air dried and passed through a 2mm sieve. Five sets of eight subsamples, each equivalent to 11, 340g of oven dry soil, were fertilized with 0, 12.5, 25.0, 37.5, and 50.0 ppm K as KCl, 250.0 ppm N as $Ca(NO_3)_2.4H_2O$, 75.0 ppm P as $NaH_2PO_4.2H_2O$, 22.5 ppm Mg as $MgSO_4.7H_2O$, 12.0 ppm $ZnSO_4.7H_2O$, 12.0 ppm $CuSO_4.5H_2O$, 12.0 ppm $MnSO_4.4H_2O$, 7.5 ppm Borax and 0.25 ppm $(NH_4)_6Mo_7O_{24}.4H_2O$. The fertilized subsamples were firmly packed into 10 litre polyethylene pots. One pot at each level of K was not cropped, while the other pots were cropped with *E.curvula*, 200 seeds being planted per pot. Four replications of the K treatments were arranged in a randomised blocks design. The remaining pots were replacement after core sampling. Pots were rotated both within and between replications twice weekly and daily watered to field moisture capacity by weighing. Grass was cut 2cm above soil level just prior to flower initiation. Roots were not harvested due to the difficulties involved in soil separation and to the fact that they probably contribute little to the total K uptake in exhausted soils [<4% according to Arnold and Close (1961)]. Quantities of N, P, Ca, and Mg removed by the crop were replaced in solution form after each harvest.

Seven soil cores (± 300g) were removed from every pot at the start and after each of the first three harvests. This soil was replaced with soil from duplicate pots. Points of sampling were marked to avoid subsequent removal of soil from the same positions. Approximately half of each soil sample was air dried before analysis and the remainder analysed moist. The uncropped pots were maintained at field moisture capacity and sampled at the start of the experiment and at each harvest date to facilitate any necessary adjustment for fixation or release of K with increasing time of incubation. Soil K availability indices were correlated with cumulative yield, K% in the tissue, and cumulative K uptake.

FIELD STUDY

Soil and plant samples were obtained from a maize fertilizer experiment initiated in 1966 on an Avalon medium sandy loam near Dundee, northern Natal. Details regarding the soil, experimental design and procedure, method of sampling and sample preparation, have been described previously (chapter 2). Soil samples (0 - 15cm) were collected one month after fertilization and planting and analysed for K in the air dry state, prolonged storage being unavoidable. The aerial portions of whole plant samples were analysed for K 55, 65, 77, and 90 days after planting (see page 16) and soil K availability indices correlated with percentage K in the plants.

PLANT AND SOIL ANALYSIS

Plant extracts were prepared by ashing 2g samples at 450° and dissolution in 1+4 HCl. K, Ca, and Mg were measured flame spectrophotometrically, P was determined by the phosphomolybdovanadate method and N by the Kjeldahl procedure.

Exchangeable soil K (Kex) was determined by shaking with neutral N NH_4OAc using a 1:10 soil to solution ratio. The Q/I parameters labile pool ($-\Delta K^o$), equilibrium activity ratio (AR_o^K), and potential buffering capacity (PBC^K) were determined in accordance with the procedure outlined by Beckett (1964b). Five 10g portions of each soil sample were equilibrated overnight in an end over end shaker (12rpm) at 20° ± 1° with 50ml of 0.001 M $CaCl_2$ containing 0, 8, 20, 30, and 40 ppm of K respectively. After centrifugation K, Ca, and Mg in the supernatant were determined flame spectrophotometrically. Activity ratios (AR_e^K) of the centrifugates were computed making use of the Debye-Huckle equation. $-\Delta K^o$ and PBC^K were computed by regression of ΔKe, the gain or loss of K from the solution, on AR_e^K. Correlation coefficients were computed simultaneously as a measure of linearity. AR_o^K was obtained by division of $-\Delta K^o$ by PBC^K. The equilibration of smaller quantities of soil giving rise to the curved portion of the Q/I relationship was not undertaken as this can be attributed to exchange sites exhibiting specificity for K (Beckett, 1964c).

For the sake of convenience a modification of Woodruff's (1955) technique was used for the determination of ΔF, the energy of exchange for the replacement of Ca by K. These values were calculated from activity ratios obtained after equilibration with the K free solution in Q/I analysis.

K potential as defined by Zandstra and MacKenzie (1968) ($-\Delta K^o \times PBC^K$) was given the notation K index A, the multiple correlation of AR_o^K and PBC^K on plant K or yield, as used by Barrow (1967), K index B and that using $-\Delta K^o$ and AR_o^K, K index C.

RESULTS

Despite top grain yields in the field experiment in excess of 9,500 kg/ha and the absence of significant yield responses to K, all treatments in the pot experiment were K deficient after the first harvest. At this stage soil K status of pots receiving the highest K application had been reduced below the unfertilized level, which was K deficient during the first cropping (tables 11 and 12). The

Table 11 Potassium availability indices in an Avalon medium sandy loam as affected by K fertilization and cropping in pots with <u>E. curvula</u>

Sampling stage	K applied (mg/pot)	K availability index: $-\Delta K^o$ (me%)		AR_o^K $[M^{\frac{1}{2}}]$		ΔF (cals/equiv.)		Kex (me%)	
		moist	air dry	moist	air dry	moist	air dry	moist	air dry
At start	nil	.13	.14	.028	.025	-3163	-3097	.15	.15
	141.8	.16	.15	.031	.030	-3021	-3001	.18	.20
	283.6	.20	.19	.035	.038	-2915	-2892	.21	.22
	425.4	.23	.21	.042	.043	-2838	-2816	.25	.24
	567.2	.27	.24	.045	.056	-2765	-2744	.28	.28
At 1st harvest	nil	.05	.05	.007	.007	-3698	-3728	.06	.10
	141.8	.05	.04	.008	.007	-3708	-3686	.08	.08
	283.5	.06	.05	.009	.008	-3545	-3640	.09	.13
	425.4	.09	.07	.015	.012	-3372	-3468	.11	.11
	567.2	.10	.09	.015	.013	-3332	-3377	.12	.13
At 2nd harvest	nil	.01	.05	.001	.003	-4515	-3698	.04	.04
	141.8	.01	.01	.001	.001	-4372	-4255	.04	.05
	283.6	.01	.04	.001	.003	-4209	-4073	.04	.04
	425.4	.01	.05	.002	.004	-4316	-4003	.04	.04
	567.2	.02	.03	.003	.002	-4127	-3964	.05	.04

only visible symptom of deficiency up to the fourth harvest was early wilting. During the fourth crop, however, all plants developed a weak chlorotic appearance, lower stems and leaf sheaths being worst affected. In addition regrowth was poor and a high percentage of plants failed to

Table 12 Effects of differential K fertilization on yield, K uptake, and percentage K in five cuttings of E. curvula

Date of harvest	K applied (mg/pot)	Mean yield oven dry material (g/pot)	Mean K uptake (mg/pot)	Mean K percent in oven dry material
6/11/67	nil	29.35	333	1.13
	141.8	29.11	348	1.19
	283.6	31.05	375	1.20
	425.4	31.79	416	1.31
	567.2	32.04	491	1.53
		SE = 0.49	SE = 15	SE = 0.05
		LSD = 1.51(5%)	LSD = 46(5%)	LSD = 0.16(5%)
		2.10(1%)	64(1%)	= 0.22(1%)
14/12/67	nil	31.60	266	0.85
	141.8	32.33	300	0.93
	283.6	32.02	321	1.00
	425.4	33.85	387	1.14
	567.2	32.78	397	1.22
		SE = 0.71	SE = 9	SE = 0.03
		LSD = 2.16(5%)	LSD = 27(5%)	LSD = 0.07(5%)
		3.01(1%)	37(1%)	0.10(1%)
12/1/68	nil	28.37	167	0.59
	141.8	27.99	172	0.62
	283.6	31.21	211	0.68
	425.4	30.75	235	0.76
	567.2	31.81	270	0.85
		SE = 0.75	SE = 5	SE = 0.01
		LSD = 2.30(5%)	LSD = 15(5%)	LSD = 0.04(5%)
		3.22(1%)	21(1%)	0.05(1%)
19/2/68	nil	24.56	77	0.30
	141.8	25.06	78	0.31
	283.6	23.95	82	0.35
	425.4	24.05	90	0.37
	567.2	26.06	108	0.42
		SE = 0.88	SE = 3	SE = 0.01
		LSD = 2.70 (5%)	LSD = 8(5%)	LSD = 0.04(5%)
		3.76(1%)	11(1%)	0.06(1%)
28/3/68	nil	11.89	40	0.31
	141.8	11.50	40	0.35
	283.6	11.82	43	0.36
	425.4	13.76	53	0.39
	567.2	14.29	59	0.41
		SE = 0.83	SE = 2	SE = 0.02

Applications of K after termination of the experiment resulted in rapid regrowth. Although the soil tests used failed to detect significant differences between treatments after the second cut and yield differences were irregular after the first harvest, significant and consistent differences in K content and uptake were evident up to the final harvest (tables 11 and 12).

Correlation coefficients established between the various soil K indices measured and cumulative yield of E. curvula, K% in the tissue at five cuts, and cumulative K uptake indicated that predictability generally decreased in the order cumulative K uptake > K percent > cumulative yield (tables 13, 14, and 15). After the second cut K percent in the tissue correlated best with soil test, probably due to the very similar yields obtained. Although correlations obtained using moist soil samples indicated that all parameters measured provided essentially similar indices of K availability, the curves in figure 5

Table 13 Correlation coefficients relating K availability indices on moist and air dry soil samples to cumulative K uptake by E. curvula in pots

Number of Crops	Kex (me%)	$-\Delta K^o$ (me%)	AR^K_o $[M^{\frac{1}{2}}]$	K index A $[(me\%)^2 \times M^{-\frac{1}{2}}]$	K index B	K index C	ΔF (cals/ equiv.)
				Moist samples			
1	.7800	.7842	.7706	.7427	.7707	.7918	.7487
2	.9116	.8957	.9130	.8911	.8900	.9132	.8720
3	.9570	.9439	.9548	.9438	.9547	.9550	.9176
4	.9561	.9529	.9638	.9449	.9637	.9649	.9238
5	.9680	.9549	.9672	.9471	.9671	.9681	.9251
				Air dry samples			
1	.7433	.7891	.8043	.5759	.8085	.8084	.7497
2	.7867	.8865	.9030	.7074	.9034	.9113	.8788
3	.8964	.9424	.9496	.7652	.9495	.9277	.9356
4	.9061	.9503	.9611	.7640	.9610	.9503	.9421
5	.8854	.9624	.9639	.7639	.9638	.9646	.9439

n = 18. Values required for significance = .4438 (P = 0.05)

Table 14 Correlation coefficients relating K availability indices on moist and air dry soil samples to percentage K in <u>E. curvula</u> in pots

Number of Crops	Kex (me%)	$-\Delta K^{o}$ (me%)	AR_{o}^{K} $[\underline{M}^{\frac{1}{2}}]$	K index A $[(me\%)^{2} \times \underline{M}^{-\frac{1}{2}}]$	K index B	K index C	ΔF (cals/equiv.)
				Moist samples			
1	.7677	.7597	.7608	.7150	.7665	.7641	.7124
2	.9495	.9342	.9515	.9408	.9464	.9516	.9274
3	.8998	.9058	.9198	.8982	.9140	.9206	.8731
4	.8705	.8656	.8652	.8519	.8467	.8606	.8297
5	.7469	.7470	.7396	.7381	.7368	.7482	.7480
				Air dry samples			
1	.7398	.7405	.7930	.4948	.7864	.8143	.7234
2	.9043	.9261	.9261	.7628	.9490	.9310	.9375
3	.8551	.9060	.9175	.7262	.9081	.9183	.8857
4	.8094	.8697	.8768	.7113	.8757	.8782	.8502
5	.7280	.7454	.7356	.5839	.7481	.7365	.7472

Table 15 Correlation coefficients relating K availability indices on moist and air dry soil samples to cumulative yield of <u>E. curvula</u> in pots

Number of Crops	Kex (me%)	$-\Delta K^{o}$ (me%)	AR_{o}^{K} $[\underline{M}^{\frac{1}{2}}]$	K index A $[(me\%)^{2} \times \underline{M}^{-\frac{1}{2}}]$	K index B	K index C	ΔF (cals/equiv.)
				Moist samples			
1	.5662	.5625	.5287	.5846	.5437	.5625	.5556
2	.5350	.5206	.5441	.5571	.5768	.5464	.5360
3	.6418	.6404	.6412	.6666	.6620	.6441	.6434
4	.6882	.6876	.6843	.6917	.6840	.6897	.6747
5	.7632	.7523	.7651	.7609	.7646	.7654	.7397
				Air dry samples			
1	.4968	.5864	.5627	.5809	.5490	.5829	.5710
2	.4835	.6321	.6320	.6317	.5045	.5683	.5425
3	.5784	.6619	.6649	.6613	.6163	.6708	.6550
4	.6378	.6972	.6795	.6240	.6795	.6979	.6876
5	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

demonstrate a somewhat superior agreement between K applied and Kex. When soil samples were air dried prior to analysis, changes in the relationship of soil test to plant uptake were apparent (fig. 5). Marked reduction in predictability due to air drying only occurred in the cases of Kex (94% - 74%) and K index A (90% - 58%), however. The decrease in prognostic value of K index A suggested that PBC^K changes may have occurred on drying (see chapter 5). While $-\Delta K^o$, AR_o^K, and K indices B and C were not significantly affected by drying, the generally decreased values of $-\Delta K^o$ and increased values of AR_o^K on drying (fig. 5d,f) was also indicative of PBC^K changes. The experimental procedure, however, precluded a satisfactory statistical test of this effect.

While total removal of K was in excess of Kex, rate of uptake was approximately proportional to this fraction of the soil K, all pots having become depleted at almost the same time regardless of initial K status or yield of plant material (table 16).

Table 16 Influence of exchangeable K on the rate of K uptake, by five successive crops of *E.curvula* grown in pots

Native plus added K measured initially (mg/pot)	Percent of initially exchangeable K recovered in tops				
	1 Crop	2 Crops	3 Crops	4 Crops	5 Crops
665	50	90	115	127	133
798	44	81	103	113	118
931	40	75	97	106	111
1109	38	72	94	102	107
1242	39	72	93	102	107

Analysis of soil from uncropped pots indicated that meaningful release or fixation of K had not occurred over the five month period of experimentation.

Correlation coefficients established using soil and plant samples from the field experiment are presented in table 17. It is interesting

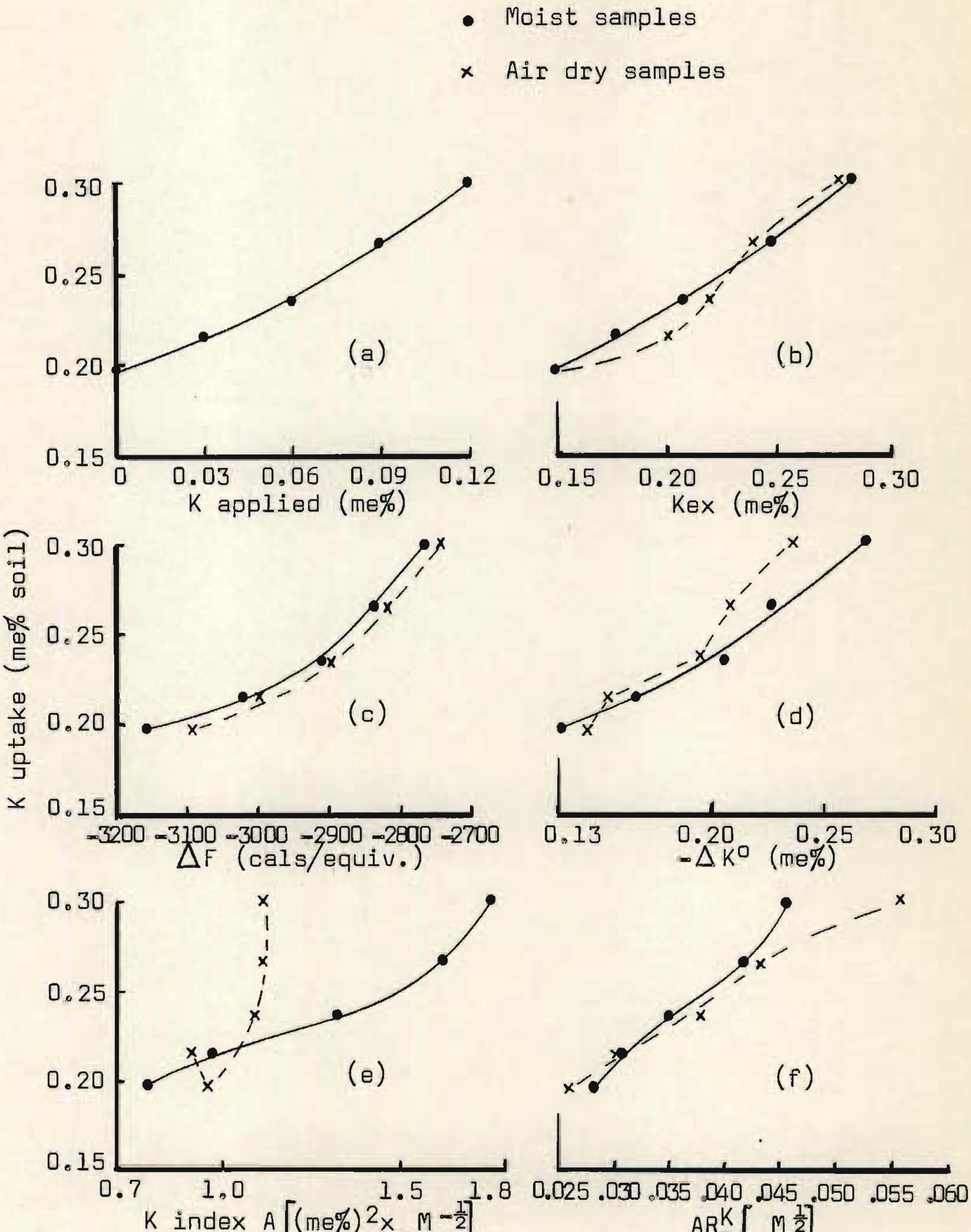


Fig. 5 Relationship between potassium uptake by <u>E. curvula</u> and six potassium availability indices

Table 17 Correlation coefficients relating K availability indices on air dry soil samples to percentage K in field maize at four sampling times.

Sampling	Days after planting	Kex (me%)	$-\Delta K^o$ (me%)	AR_o^K $[M^{\frac{1}{2}}]$	K index A $[(me\%)^2 \times M^{-\frac{1}{2}}]$	K index B	K index C	ΔF (cals/ equiv.)	K applied (kg/ha)
1st	55	.7144	.7684	.5670	.6622	.6627	.7732	.7606	.6990
2nd	65	.8096	.8350	.5788	.7309	.7360	.8367	.7877	.8025
3rd	77	.7201	.7869	.5384	.6685	.6612	.7890	.7552	.7270
4th	90	.8075	.8172	.6077	.7165	.7073	.8234	.8050	.8169

n = 79. Values required for significance = .2172 ($P = 0.05$)
.2830 ($P = 0.01$)
.3568 ($P = 0.001$)

dried and that the stress on K reserves must necessarily have been considerably less, since there was no yield response to K (chapter 2), the value of Kex relative to the other parameters was somewhat greater than where dry samples were used in the pot trial. While correlation coeffecients obtained using Kex, $-\Delta K^o$, and K index C were not significantly different, the prognostic values of AR_o^K, K index A, and K index B were all significantly inferior. The decrease in the prognostic value of AR_o^K was especially marked. It is particularly noteworthy that, as was the case in pot experimentation, the prognostic value of K index A was poor relative to $-\Delta K^o$. This again indicated that PBC^K was not constant. The consistent superiority of K index B over AR_o^K also suggested a meaningful relationship between K status and PBC^K.

DISCUSSION

In both field and glasshouse studies Kex provided a satisfactory index of plant available K and use of more laborious and complicated techniques based on the concept of nutrient potential does not appear warranted on sandy soils of the Avalon series.

While the prognostic value of Kex was reduced in pot experimentation significant. Similar findings regarding the efficacy of Kex were reported by Barrow (1966), but it was suggested that under field conditions its importance might diminish, K supply seldom being so severely depleted as in pots. Results obtained from the field trial, however, indicated that this was not the case. The relative value of Kex was rather improved, while the importance of AR_o^K, K index A and K index B diminished significantly.

The fact that the Avalon medium sandy loam exhibits little release or fixation of K on air drying and contains abnormally low reserves of nonexchangeable K cannot be overlooked. Many Natal soils release highly significant amounts of K on air drying and the efficacy of exchangeable K as an index of K availability may conceivably be affected to a greater degree than techniques involving the measurement of nutrient potentials. Most Natal soils, however, also contain meaningful quantities of nonexchangeable K and if the efficacy of Kex is likely to decrease in such soils (Fraps, 1929; Pratt, 1951; Acquaye, MacLean and Rice, 1967), the value of indices involving the measurement of labile pool ($-\Delta K^o$) will in all probability diminish further, labile pool representing a less firmly held portion of the soil K. Evidence substantiating this surmise has been obtained in subsequent work (chapter 4).

A detailed study of the soil used in this work has shown that the PBC^K is significantly altered by both air drying and K fertilization (chapter 5) and results of both the glasshouse and field experiments suggest that such changes are meaningful with regard to the prediction of K requirements. While PBC^K changes have also been noted by Beckett (1964b), Beckett <u>et al.</u>, (1966) and Beckett and Nafady (1967), such changes have not previously been considered meaningful. It is noteworthy, that no changes in pH, a factor known to alter the form of the Q/I relationship in soils with pH dependent charge (Tinker, 1964), were detected in either the glasshouse or field studies.

Incidental information, which has emerged from these investigations, suggests that field crops probably draw extensively on subsoil K reserves.

(0 - 15cm) of plots not fertilized with K by an amount greater than the first crop of <u>E. curvula</u> (fig. 2), yield responses were not recorded until the fourth season. Since the first grass cut was obtained after 76 days, a period of time closely approximating the active uptake period of field maize, and roots had not yet fully exploited the available rooting volume, marked demand differences can be discounted. Furthermore, as K release from nonexchangeable sources in the field was, after two seasons, similar to that recorded in pots (tables 6 and 16), differences were apparently not due to any inherent ability of maize to extract K more efficiently.

Since all K treatments in pot experimentation became depleted at approximately the same time regardless of initial K status (table 16) and applications in excess of 284 mg/pot produced no significant increase in yield (table 12), there appears to be little advantage in attempting to build up K reserves in the surface horizon of soils of this type.

CHAPTER 4

POTASSIUM AVAILABILITY IN THE PROFILE OF AN AVALON MEDIUM SANDY LOAM AS MEASURED BY SEVERAL SOIL TEST METHODS AND EXHAUSTIVE CROPPING IN POTS

INTRODUCTION

Evidence obtained from field and pot studies (chapters 2 and 3) has shown that maize grown on an Avalon medium sandy loam is capable of obtaining considerable quantities of K from below 15cm, the sampling depth commonly used in Natal for determining soil fertility requirements. Leaching studies have also demonstrated rapid vertical movement of applied K under field conditions (chapter 2), and it is considered that tests on soils of this type may not prove meaningful unless subsoil K status is taken into account.

In field and glasshouse comparisons using topsoil (0 - 15cm) techniques proposed by Beckett (1964b) and Woodruff (1955), which involve the determination of activity ratios ($^{a}K/\sqrt{^{a}Ca + {^{a}Mg}}$), provided very similar indices of K availability to the classical empirical extraction with neutral N NH_4OAc (chapter 3). Preliminary analyses by these methods, of soil samples taken down the profile and which were considered to comply with the requirement of comparable Ca and Mg status (Beckett, 1964b), however, resulted in significantly different measures of K status. Whereas N NH_4OAc extractions indicated that K status below 60cm was considerably higher than in the topsoil (0 - 15cm), both pool of labile K($-\Delta K^{o}$) and equilibrium activity ratio (AR_{o}^{K}), measured using the quantity-intensity (Q/I) technique (Beckett, 1964b) and intensity measured as the energy of replacement of Ca by K (ΔF) as suggested by Woodruff (1955), failed to indicate this.

Barrow (1966) has demonstrated the need to also consider the soils capacity to resist a change in potential (Beckett's potential buffering capacity or PBC^{K}). Even joint consideration of $-\Delta K^{o}$ and PBC^{K}, however, failed to entirely reconcile these differences.

Clearly, if subsoil horizons are considered information already (chapter 3) is of little value and the effects of physical and chemical changes down the profile on indices of K availability will have to be assessed.

According to Le Roux and Sumner (1968) results obtained using empirical extraction techniques are of little value in Natal, due to the large variation in soils over relatively short distances. There is, however, little experimental evidence to support this claim. Furthermore, although these authors have shown that the Q/I parameters $-\Delta K^{0}$ and AR_{0}^{K} are closely related to level of applied K, techniques involving intensity measurements have not yet been shown to lead to any marked improvement in the diagnosis of fertility (Barrow, 1967; Koch, 1968; Zandstra and MacKenzie, 1968).

The purpose of this study was to compare K availability indices supplied by empirical extractions using N NH_4OAc at pH_7, 0.01 M $CaCl_2$, 0.001 M $CaCl_2$ and N HNO_3 with indices obtained from techniques involving intensity measurements in six horizons of an Avalon medium sandy loam.

MATERIALS AND METHODS

Six bulk soil samples were collected in 15cm increments to a depth of 90cm from a site adjacent to that used in previous field and pot studies (chapters 2 and 3). Samples were air dried and ground to 2mm with a wooden roller, care being taken to retain all plinthite present in subsoil horizons. Although hard after exposure to the atmosphere, this plinthite was soft and considered an active part of the soil matrix *in situ*. Soils were analysed air dry as K release/fixation had previously been shown to be negligible when samples were not fertilized with K. After thorough mixing, each bulk sample was sub-sampled and the following K availability indices determined.

1. Neutral N NH_4OAc exchangeable K (Kex) as described earlier (chapter 2).

2. Percentage K saturation of the exchange complex.

previously (chapter 3) and a constant soil : solution ratio of 1:5.

4. Equilibrium activity ratio (AR_o^K) obtained in (3) above.

5. The energy of exchange of Ca by K (ΔF) obtained from the minus K solution in (3) as described earlier (chapter 3).

6-10. K extractable with 0.001 M $CaCl_2$ after 8 hours shaking end over end with soil : solution ratios of 1:10, 1:25, 1:50, 1:75, and 1:100.

11. K extractable with 0.01 M $CaCl_2$ after 8 hours shaking end over end with a soil : solution ratio of 1:100.

12. N HNO_3 releasable K determined as described previously (chapter 2).

13. K index A ($-\Delta K^o \times PBC^K$) obtained from values established in (3) above.

Equilibrations with 0.001 M $CaCl_2$ in soil : solution ratios of 1:10, 1:25, and 1:50 were also used to obtain the curved portion of the Q/I relationship by computing ΔK_e and AR_e^K values as in (3) and (4).

Six portions of each soil horizon equivalent to 1250g of oven dry material were placed in one litre polyethylene pots after thorough mixing with 250 ppm N as NH_4NO_3, 100 ppm P as $Ca(H_2PO_4)_2.2H_2O$, 12 ppm $ZnSO_4.7H_2O$, 12 ppm $CuSO_4.5H_2O$, 12 ppm Borax and 0.25 ppm $(NH_4)_6 Mo_7O_{24}.4H_2O$. A further 250 ppm N was applied after the second cut. One hundred rye grass seeds (Lolium perene cv Ariki) were planted per pot and the pots arranged in a Latin square design. All pots were watered to field moisture capacity twice daily by weighing until after the third cut. From this stage, due to the greatly reduced growth rate, only a single watering per day was necessary. Grass was cut approximately 1cm above soil level when the best plants had attained a length of approximately 15cm. Harvested plant material was dried in a forced draught oven at 90^o, weighed and milled. K content of the plant tissue was determined flame spectrophotometrically after 30 minutes extraction of 0.2g with 50ml N NH_4OAc. Cumulative K uptake by the rye grass was correlated with the K indices measured. In addition multiple correlations were calculated between K uptake and AR_o^K and PBC^K (K index B) and K uptake and $-\Delta K^o$ and AR_o^K (K index C).

Pertinent physical and chemical properties of the six horizons have been presented elsewhere (table 3).

RESULTS

Notwithstanding marked yield differences, which first became apparent shortly after germination, characteristic K deficiency symptoms did not appear until the third cropping, during which plants in the two surface horizons died (plate 4).

Plate 4 Growth of L. perene in six horizons of an Avalon medium sandy loam immediately prior to the third cut

Although yield and K uptake by plants in the two deepest horizons tissue had dropped to virtually the same level in all pots by the third cut (table 18).

Table 18 Mean dry matter yield, K percent, and K uptake by three crops of L. perene grown in six horizons of an Avalon medium sandy loam

Days after Planting	Soil horizon (cm)	Yield (g/pot)	K%	K uptake (mg/pot)
48	0-15	1.75	2.57	44.5
	15-30	1.47	2.53	37.0
	30-45	1.24	2.43	29.9
	45-60	1.15	2.30	25.8
	60-75	2.44	2.89	70.4
	75-90	3.70	3.31	122.3
		SE = 0.050	SE = 0.084	SE = 1.49
		LSD = 0.14(5%)	LSD = 0.24(5%)	LSD = 4.5(5%)
		0.20(1%)	0.34(1%)	6.0(1%)
82	0-15	2.52	1.03	26.0
	15-30	2.21	1.37	29.9
	30-45	1.50	1.38	20.6
	45-60	1.54	1.40	19.1
	60-75	3.66	1.51	53.5
	75-90	4.43	1.74	76.8
		SE = 0.103	SE = 0.050	SE = 0.82
		LSD = 0.30(5%)	LSD = 0.15(5%)	LSD = 2.4(5%)
		0.42(1%)	0.20(1%)	3.5(1%)
126	0-15	1.30	0.92	12.0
	15-30	1.28	1.01	13.0
	30-45	1.42	1.06	14.1
	45-60	1.69	0.88	14.4
	60-75	5.43	0.88	47.7
	75-90	7.76	0.94	72.9
		SE = 0.183	SE = 0.027	SE = 1.63
		LSD = 0.53(5%)	LSD = 0.19(5%)	LSD = 4.7(5%)
		0.74(1%)	0.27(1%)	6.6(1%)

In the first three crops uptake of K appeared to be roughly proportional to Kex, similar percentages of this pool being removed by each crop (table 19).

Plants growing in the 30-45cm and 45-60cm horizons died after

Table 19 Cumulative K uptake by L. perene grown on six horizons of an Avalon medium sandy loam and percentage of total K obtained from initially nonexchangeable sources

Soil horizon (cm)	Kex in uncropped soil (mg/pot)	Cumulative K uptake (mg/pot)*							Percentage† K released
		1 crop	2 crops	3 crops	4 crops	5 crops	6 crops	7 crops	
0-15	78	45	71	83					6.4
15-30	73	37	67	80					9.6
30-45	68	30	51	65	67	68			-
45-60	58	26	45	59	63	67			15.5
60-75	169	70	124	172	188	198	206	208	23.1
75-90	271	122	199	272	297	312	324	328	21.0

* 1mg K/pot contained in seed

† excludes K contained in roots

after the seventh crop. Presumably growth after the third cut was sustained by release from originally nonexchangeable sources. Such release increased markedly below 45cm and was in excess of 20% in the two deepest horizons (table 19).

Indices of K availability are presented in table 20 and correlations between these and plant uptake in table 21.

Kex proved to have the best prognostic value. N HNO_3 releasable K did not initially prove to be significantly correlated with uptake, but not unexpectedly provided an improved index as K depletion progressed and initially nonexchangeable K played an increasingly important rôle. Labile pool ($-\Delta K^o$) and intensity measurements (AR_o^K and ΔF) proved to have poor prognostic value. Q/I parameters considered jointly (K indices A, B, and C), however, provided greatly improved measures. The superiority of K indices involving PBC^K measurements (K indices A and B) over that derived from joint consideration of labile pool and equilibrium activity ratio (K index C) was probably due to the compounded errors produced in these two parameters by slight errors in the determination of PBC^K.

Although labile pool values established by linear extrapolation

Table 20 Thirteen indices of K availability in six horizons of an Avalon medium sandy loam

K availability index	Soil depth increment						Units
	0–15	15–30	30–45	45–60	60–75	75–90	
Kex	0.16	0.15	0.14	0.12	0.36	0.58	me%
$-\Delta K^{o}$	0.13	0.08	0.10	0.02	0.08	0.17	"
AR^{K}_{o}	0.0219	0.0182	0.0112	0.0014	0.0037	0.0071	$\underline{M}^{\frac{1}{2}}$
ΔF	–2975	–3165	–3280	–3960	–3480	–3145	cals/equiv.
$-\Delta K^{o} \times PBC^{K}$	0.81	0.35	0.89	0.23	1.83	4.38	$(me\%)^{2} \times \underline{M}^{-\frac{1}{2}}$
0.01 $\underline{M}$ $CaCl_2$ 1:100	0.15	0.13	0.10	0.05	0.13	0.26	me%
0.001 $\underline{M}$ $CaCl_2$ 1:10	0.15	0.10	0.07	0.03	0.05	0.08	"
0.001 $\underline{M}$ $CaCl_2$ 1:25	0.19	0.11	0.08	0.03	0.11	0.13	"
0.001 $\underline{M}$ $CaCl_2$ 1:50	0.19	0.15	0.10	0.04	0.17	0.17	"
0.001 $\underline{M}$ $CaCl_2$ 1:75	0.17	0.15	0.14	0.10	0.15	0.23	"
0.001 $\underline{M}$ $CaCl_2$ 1:100	0.18	0.15	0.13	0.10	0.16	0.23	"
$\underline{N}$ HNO_3 releasable	0.20	0.21	0.28	0.41	0.60	0.74	"
% K saturation	9.9	8.9	4.3	2.6	4.3	6.4	

have resulted if K held at sites showing a more specific affinity for K and represented by the curved portion of the Q/I relationship (Beckett, 1964c) had been taken into account (fig. 6). It was considered, however, that the asymptotic extrapolations required to obtain these values would have been subject to unacceptable error.

$CaCl_2$ equilibrations failed to indicate that the 60 – 75cm horizon contained significantly greater quantities of plant available K than the surface horizon. Even in the first crop, however, uptake from the deeper horizon was significantly (P = 0.01) greater (table 18).

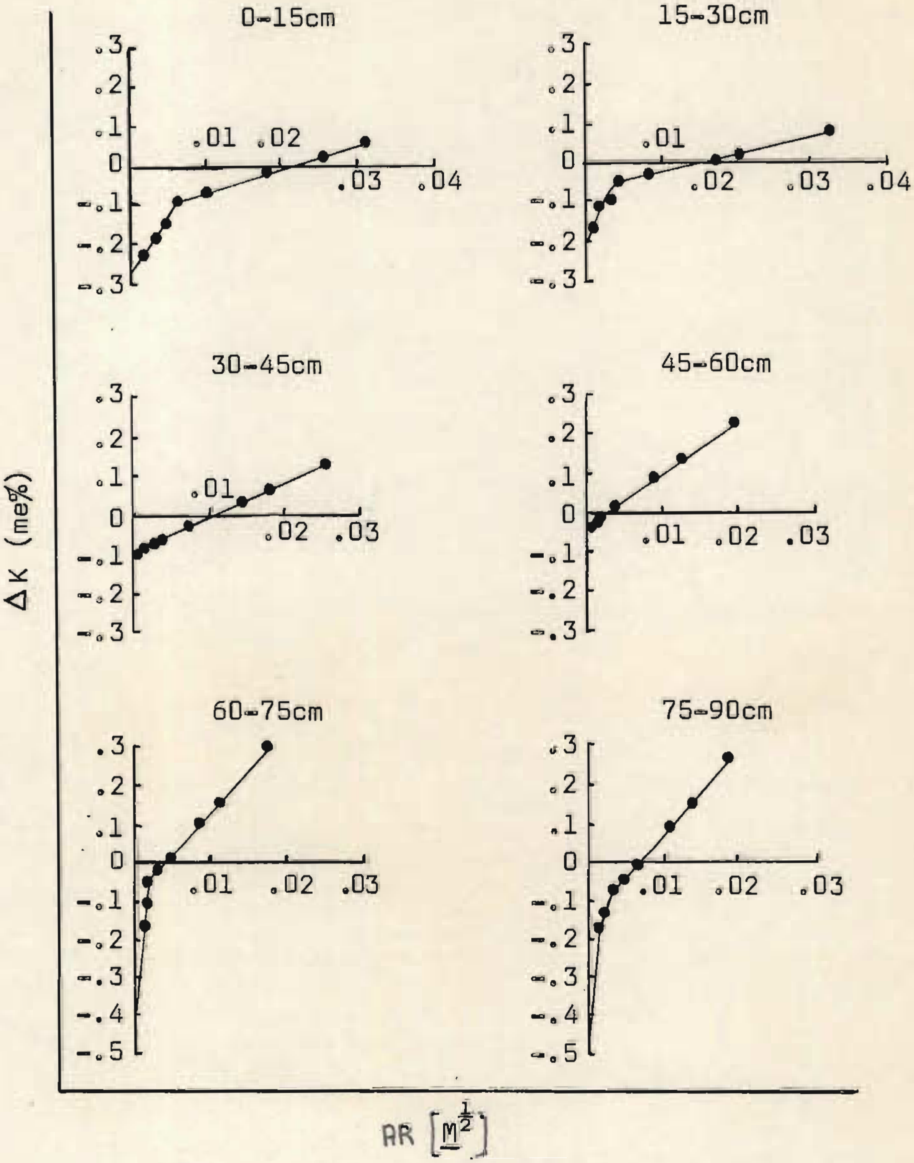


Fig. 6 Quantity-intensity relations in six horizons of an Avalon medium sandy loam

Table 21 Correlation coefficients relating soil K availability indices to cumulative uptake by L. perene

K availability index	Number of crops						
	1	2	3*	4	5†	6	7
Kex	.9909	.9951	.9989	.9994	.9991	.9989	.9899
$-\Delta K^o$	ns						
AR^K_o	ns						
ΔF	ns						
K index A	.9798	.9712	.9718	.9713	.9698	.9687	.9688
K index B	.9643	.9847	.9709	.9730	.9738	.9748	.9747
K index C	.9229	.9070	.9139	.8660	.9195	.8586	.8588
0.001 M $CaCl_2$ 1:100	.8827	.8656	.8320	.8183	ns		
0.001 M $CaCl_2$ 1:75	.8823	.8614	.8304	.8160	ns		
0.01 M $CaCl_2$ 1:100	.9133	.8965	.8676	.8536	.8430	.8400	.8398
N HNO_3 releasable	ns	.8513	.8818	.9012	.9018	.9041	.9044
% K saturation	ns						

0.8114 P = 0.05, 0.9172 P = 0.01, 0.9701 P = 0.001

* growth ceased in 0 - 15cm and 15 - 30cm horizons

† growth ceased in 30 - 45cm and 45 - 60cm horizons

unrelated to plant uptake.

DISCUSSION

The main aim of this study was to determine what influence subsoil sampling of an Avalon medium sandy loam has on the efficacy of a number of soil testing techniques.

The data reported indicate that Kex provides an excellent index of plant availability that is practically unaffected by mechanical and

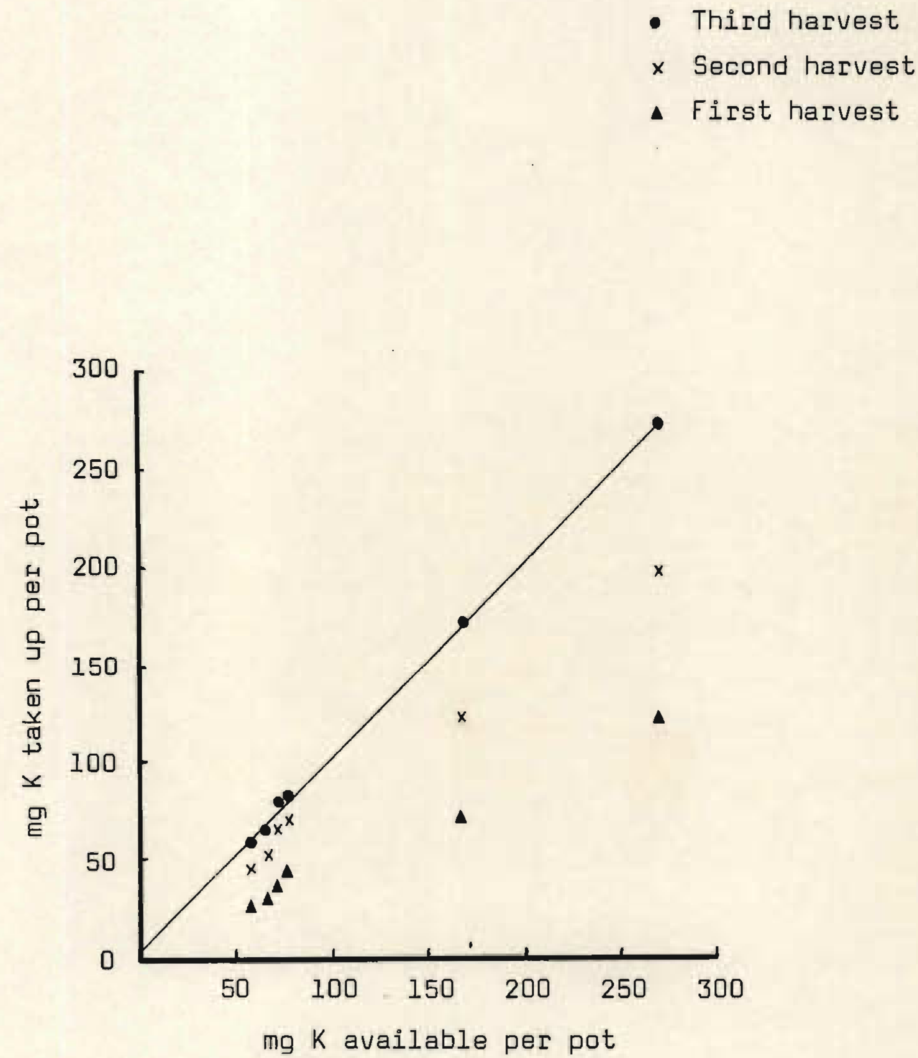


Fig. 7 Relationship existing between K extractable with N NH_4OAc at pH7 and cumulative K uptake by L. perene

acceptable index, all that is usually expected of a soil test, but proved to be closely related quantitatively to cumulative plant uptake by the time deficiency symptoms first appeared (fig. 7). This supports the view that Kex represents that portion of the soil K readily available to plants (Wiklander, 1958). Plants take up the bulk of their nutrient requirements from the soil solution, supply to root surfaces being largely dependent upon diffusion or exchange diffusion (Barber, 1968). Where the supply of K is low the relative importance of exchange diffusion, the interdiffusion of K with another ion such as H_3O^+ moving away from the root, increases. H_3O^+ and NH_4^+ ions are thought to have similar abilities to replace K^+ in the clay lattice (Rich, 1964) and the proportion of K^+ ions replaceable by N NH_4OAc is probably similar to that replaceable by H_3O^+ ions generated at root surfaces.

In this respect results obtained are consistent with the findings of plant physiologists in which uptake has been shown to be approximately proportional to the K concentration in solution (Nye, 1968).

Individual quantity ($-\Delta K^0$) and intensity (AR_0^K and ΔF) parameters on the other hand, proved to be poorly related to plant uptake, even though these values were well correlated with plant uptake when only topsoil was considered (chapter 3). Use of quantity and intensity parameters independently, however, although not an uncommon practice, is not justified unless capacity factors are fairly constant. These parameters are not universal functions of plant available K and when used without a capacity factor must reduce the Q/I approach to the same level of empiricism as techniques involving normalised electrolytes. As such they are subject to the very problems of localised significance this approach was presumably developed to overcome. Results presented demonstrate the importance of considering a capacity factor and support the findings of Barrow (1966) and Zandstra and MacKenzie (1968).

Even joint consideration of any two Q/I parameters, sufficient to characterise a soil with regard to the supply of K and the soil's labile pool ($-\Delta K^{o}$) and intensity, expressed either as equilibrium activity ratio (AR_{o}^{K}) or the free energy of exchange of K for Ca (ΔF), are uniquely related to plant availability. There is, however, little evidence to indicate that this is the case. The results of much correlative work purporting to provide evidence for this belief (Barrow, 1966; Le Roux and Sumner, 1968; Koch, 1968) are confounded somewhat by the overwhelming importance of very readily available fertilizer K or the absence of significant quantities of less available adsorbed K.

Beckett (1964b) has stated that the form of the Q/I relationship almost certainly regulates the uptake of K over short periods. The fact that when the first cut was taken roots in duplicate pots had not yet exploited the whole rooting volume, however, suggests that regardless of the veracity of this statement, such periods are so short as to be of little practical significance. At this stage plants had not depleted the total labile pool of K originally available in the surface horizon, but had exhausted that originally present in the 60 - 75cm horizon. Yet uptake from the deeper horizon was considerably greater (table 19). It would consequently appear that any "short term" Q/I dependency is likely to be overshadowed in a soil-plant system by non Q/I dependent "long term" uptake. The statement that response to K under field conditions will depend mainly on the labile pool at the beginning of the season (Le Roux and Sumner, 1968) must then be considered questionable. This, it is considered, is only likely to be the case where soils have little capacity for K release or fixation, such as the surface horizon of the soil investigated here, where fertilizer K is of overriding importance or where soils have a similar PBC^{K}, in which case labile pool measurements provide a satisfactory specific index of some larger pool. Approximate agreement between Kex and pool estimated by asymptotic extrapolation of the Q/I curves established for the six horizons described here is evidence of some such larger critical pool. Labile pool established by linear extrapolation in the Q/I relationship appears to be merely an index of plant available K, which generally diminishes in relation to actual pool with increase in clay percentage

There is little evidence to support the view that plant uptake of K is dependent upon the ratio $^{a}K/\sqrt{^{a}Ca + ^{a}Mg}$, a basic assumption about which the application of techniques involving intensity measurements necessarily hinge. On the contrary, there is considerable evidence to indicate that K uptake is either unaffected or enhanced by increased concentrations of Ca (Peech and Bradfield, 1943; Viets, 1944; Van Itallie, 1938, 1948; Overstreet, Jacobson and Handley, 1952; York, Bradfield and Peech, 1953; Fawzy, Overstreet and Jacobson, 1954; Jacobson, Moore and Hannapel, 1960; Waisel, 1962). Divalent ions apparently affect the selective permeability of the outer protoplasmic barrier of cells involved in ion uptake (Waisel, 1962). Furthermore, recent work by Conyers and McLean (1969) has shown that sand dilution may cause intensity measurements to reverse direction while plant uptake continues to decrease.

Correlations between $\underline{N}$ HNO_3 releasable K and plant uptake improved with time as initially nonexchangeable K played an increasingly important rôle and it is possible that under field conditions, when growth rate and rooting intensity are considerably lower, the importance of such sources of K would be increased. Pot techniques will not, however, distinguish between releases of less readily available K, which may contribute towards maximum field crop growth and those which occur only at starvation levels.

CHAPTER 5

EFFECTS OF K RELEASE AND FIXATION ON QUANTITY-INTENSITY RELATIONS IN AN AVALON MEDIUM SANDY LOAM

INTRODUCTION

The importance of K release and fixation in the dynamics of soil K has long been recognised. Clay type, moisture content, percentage K saturation, temperature, and time are some of the factors thought to be intimately involved (Leubs, Stanford, and Scott, 1956; De Mumbrum and Hoover, 1958; Mortland, 1958; Matthews and Sherell, 1960; Haagsma and Miller, 1963).

Rapid vertical movement of applied K, marked luxury consumption and small release of K in pots cropped to exhaustion with rye grass, suggested that release and fixation of N NH_4OAc exchangeable K was of little practical signicance in an Avalon medium sandy loam (chapters 2, 3, and 4). Nevertheless, K equilibrium shifts, which occurred on air drying soil from pots and field plots differentially fertilized with K, were large enough to adversely affect the prognostic value of soil tests (chapter 3). There was evidence that the form of the K: (Ca + Mg) exchange isotherm was affected. Using Beckett's (1964a,b) quantity-intensity (Q/I) technique, high levels of K fertilization appeared to result in a reduction in potential buffering capacity (PBC^K), while air drying lead to changes in the labile pool of K ($-\Delta K^o$) and the equilibrium activity ratio (AR_o^K) sufficiently dispro-portionate to significantly reduce the value of Zandstra and MacKenzie's (1968) K potential ($-\Delta K^o \times PBC^K$) (chapter 3).

Differences in the form of the Q/I relationship between K depleted and K fertilized plots have been reported (Matthews and Beckett, 1962). It is generally considered, however, that the slope of the linear portion of the Q/I relationship or potential buffering affected by K fertilization or depletion, by fixation of added K, or by the release or fixation of K on air drying (Beckett, 1964b; Beckett et al., 1966; Beckett and Nafady, 1967a; Moss, 1967).

The aim of this study was to promote K equilibrium shifts by fertilizing with K, incubating for various periods at different moisture contents, and air drying prior to analysis, and to ascertain whether release and fixation phenomena do, in fact, significantly alter the Q/I relations of an Avalon medium sandy loam.

MATERIALS AND METHODS

Topsoil (0 - 15cm), collected from a site adjacent to that used in the field and pot studies described previously (chapters 2, 3, and 4), was air dried, ground to < 2mm, and thoroughly mixed. The bulk sample was divided into four equal parts each of which received different levels of K as KCl (0, 0.067, 0.134, and 0.268 me%). After further careful mixing each portion was split into three equal parts which were brought to 30%, 70%, and 100% of field moisture capacity respectively. Sixteen bottles were allocated to each of the 12 K-moisture combinations, half filled with soil ($\pm$ 160g) and coded for K level, moisture content, time of incubation (2, 4, 16, and 20 weeks), and treatment prior to analysis (none and air dried), each treatment combination being duplicated. The two replications were placed on separate shelves in a constant temperature room ($20^{o} \pm 1^{o}$) and the treatments positioned randomly within each replication. Bottles were aerated twice weekly by removing the lids.

After each incubation period neutral N NH_4OAc exchangeable K (Kex) and the Q/I parameters $-\Delta K^{o}$, AR_{o}^{K}, and PBC^{K} were determined as described in chapter 3. Cation exchange capacities of 12 air dry K-moisture content combinations were also determined after each incubation period by alkali distillation of soil leached with netural N NH_4OAc. All analyses were conducted at $20^{o} \pm 1^{o}$ and the results expressed on an oven dry basis.

RESULTS

Over all levels of moisture, incubation time, and soil pretreatment, fixation of applied K in a form not exchangeable with N NH_4OAc appeared to be negligible. The average increase in Kex per 0.067 me% increment in K was 0.066 ± 0.0003 me% (table 22).

Furthermore, C.E.C. determinations indicated an average difference of only 5% between unfertilized samples and those receiving the highest level of K. This difference is probably within the limits of experimental error where C.E.C. is in the order of 2 me% (table 3). Q/I data, however, suggested that some fixation of labile K ($-\Delta K^o$) may have occurred. Apart from the consistently lower values of $-\Delta K^o$ relative to Kex, attributable to sites exhibiting specificity for K (Beckett, 1964c), the average response to K was lower 0.064 ± 0.0006 me% per 0.067 me% of K (table 22). Thus, K applications probably resulted in some increase of specifically held K and a decrease in the labile pool effective C.E.C.

While the increase in $-\Delta K^o$ with level of K was almost perfectly linear, AR_o^K values were affected nearly threefold by experimental error (table 22). A good linear relationship was obtained with data from air dry samples, however, and errors in the determination of moisture appear to have been largely responsible (fig. 8c). This source of error was aggravated by uneven moisture losses during incubation, which proved difficult to eliminate. Increases in $-\Delta K^o$ and AR_o^K were disproportionate and resulted in highly significant ($P = 0.001$) changes in the form of the Q/I relationship (table 22). Over all levels of time, moisture, and soil pretreatment, changes in PBC^K were inconsistent due to the lack of precision in the determination of AR_o^K values of moist samples. Recalculating PBC^K values from the regression of AR_o^K on K level, a vertically displaced relationship very similar to that obtained with air dry samples was obtained, however (fig. 8d).

K exhaustion may result in an increase in PBC^K, due presumably to C.E.C. increases resulting from release of nonexchangeable K (Matthews

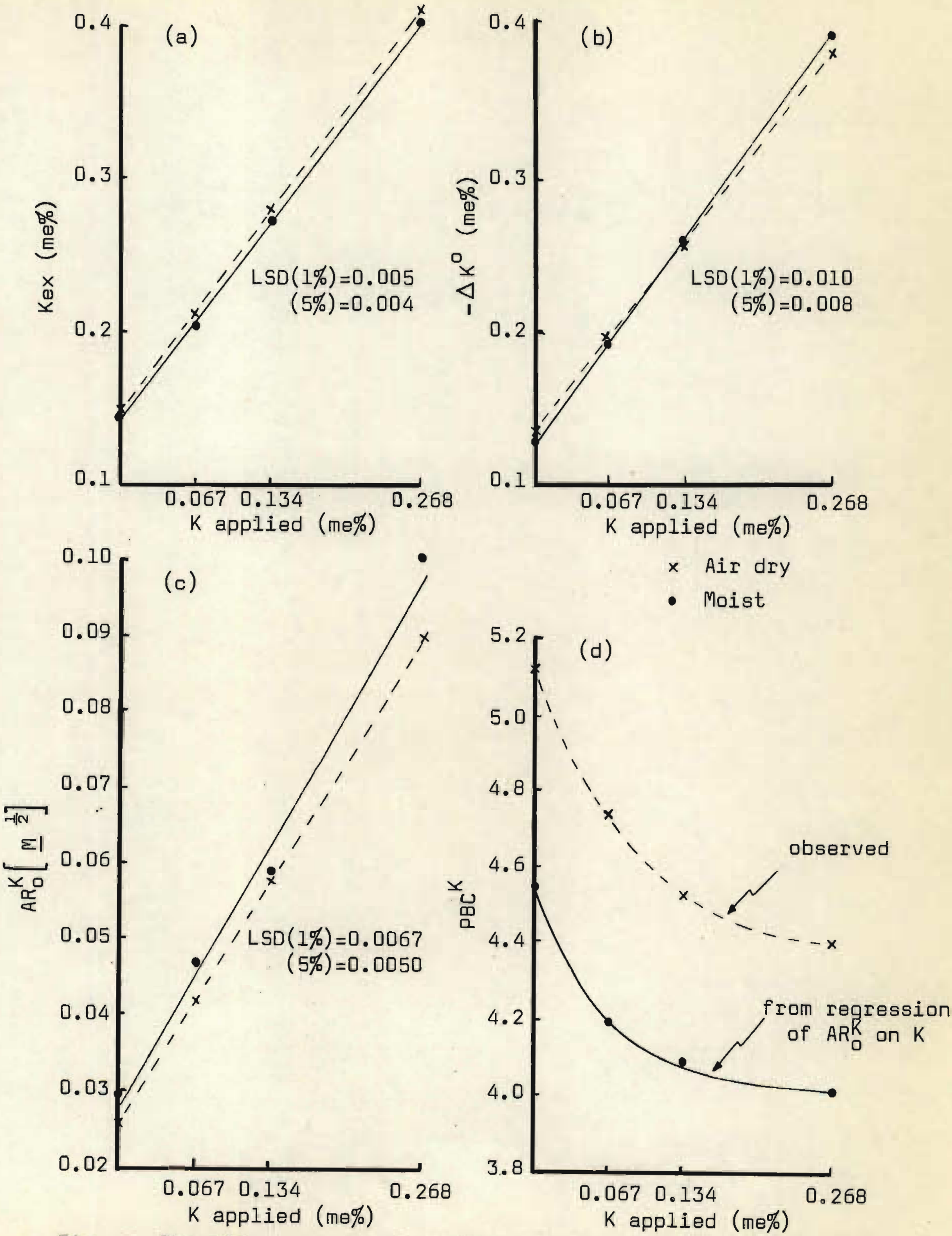


Fig. 8. The effects of level of K applied on (a) Kex, (b) $-\Delta K^o$

Table 22 The effect of K fertilization on exchangeable K (Kex) and the Q/I parameters $-\Delta K^{o}$, AR_{o}^{K}, and PBC^{K} *

K index	K applied (me%)				SE	LSD		
	nil	0.067	0.134	0.268		5%	1%	0.1%
Kex (me%)	0.145	0.206	0.276	0.406	0.0010	0.003	0.004	0.005
$-\Delta K^{o}$ (me%)	0.131	0.193	0.257	0.385	0.0019	0.005	0.007	0.009
AR_{o}^{K} $[M^{\frac{1}{2}}]$	0.0279	0.0442	0.0577	0.0953	0.00128	0.0036	0.0047	0.0061
PBC^{K}	4.77	4.45	4.55	4.20	0.078	0.22	0.29	0.37

* PBC^{K} values are from statistical analysis and differ from values calculated from $-\Delta K^{o}$ and AR_{o}^{K} means due to rounding errors in the latter

the converse, a reduction in PBC^{K} on K fertilization, has generally been ascribed to experimental error where it has been observed (Beckett _et al._, 1966; Beckett and Nafady, 1967a; Le Roux and Sumner, 1968a), the diminishing change in PBC^{K} with level of K fertilization observed in this work is consistent with such a reduction (fig. 8d). A level of K saturation was reached above which there would probably have been little further reduction in PBC^{K}, presumably due to saturation of specific exchange sites and attainment of a constant C.E.C. attributable to planar sites.

Over all levels of K, moisture content, and soil pretreatment, increase in the time of incubation resulted in a significant (P = 0.001) increase in PBC^{K} (table 23). An overall increase in $-\Delta K^{o}$ was accompanied by a decrease in AR_{o}^{K}. Although, measurements of pool (Kex and $-\Delta K^{o}$) indicated K release during incubation, no meaningful changes in C.E.C. were detected. K release would be accompanied by C.E.C. increases, however, and might result in changes in the form of the Q/I relationship consistent with those observed (Beckett, 1964b; Le Roux, 1966; Beckett and Nafady, 1967b). It is difficult to adequately explain why initial release of K should be followed by decreases in both Kex and $-\Delta K^{o}$, but an explanation is perhaps to be found in the early

Table 23 The effect of incubation time on exchangeable K (Kex) and the Q/I parameters $-\Delta K^o$, AR^K_o, and PBC^K

K index	Incubation time (weeks)				SE	LSD		
	2	4	16	20		5%	1%	0.1%
Kex (me%)	0.246	0.268	0.262	0.256	0.0010	0.003	0.004	0.005
$-\Delta K^o$ (me%)	0.228	0.240	0.257	0.241	0.0019	0.005	0.007	0.009
AR^K_o $[\underline{M}^{\frac{1}{2}}]$	0.0591	0.0604	0.0531	0.0524	0.00128	0.0036	0.0047	0.0061
PBC^K	4.15	4.17	4.85	4.79	0.078	0.22	0.29	0.37

Mumbrum and Hoover, 1958; Mortland, 1961). Moisture loss during incubation is not considered to have played a significant rôle as losses did not exceed 20% and the main effects of moisture were nonsignificant.

The response of pool (Kex and $-\Delta K^o$) and AR^K_o to time of incubation increased with level of K, resulting in a marked increase in PBC^K per two week incubation period at higher levels of K (fig. 9). Thus, the tendency for higher rates of K to decrease PBC^K tended to diminish with time. It is noteworthy, that Beckett and Nafady (1967a) observed a similar effect, heavy dressings of K leading to transient reductions in PBC^K, which were eliminated on storage.

Although, over all levels of K, moisture content, and incubation time, air drying did not alter the measured value of $-\Delta K^o$, AR^K_o was significantly ($P = 0.01$) reduced and PBC^K thus increased (table 24). Air

Table 24 The effect of air drying on exchangeable K (Kex) and the Q/I parameters $-\Delta K^o$, AR^K_o, and PBC^K

K index	Soil condition		SE	LSD		
	moist	air dry		5%	1%	0.1%
Kex (me%)	0.255	0.261	0.0010	0.003	0.004	0.005
$-\Delta K^o$ (me%)	0.241	0.241	0.0019	0.005	0.007	0.009
AR^K_o $[\underline{M}^{\frac{1}{2}}]$	0.0586	0.0539	0.00128	0.0036	0.0047	0.0061

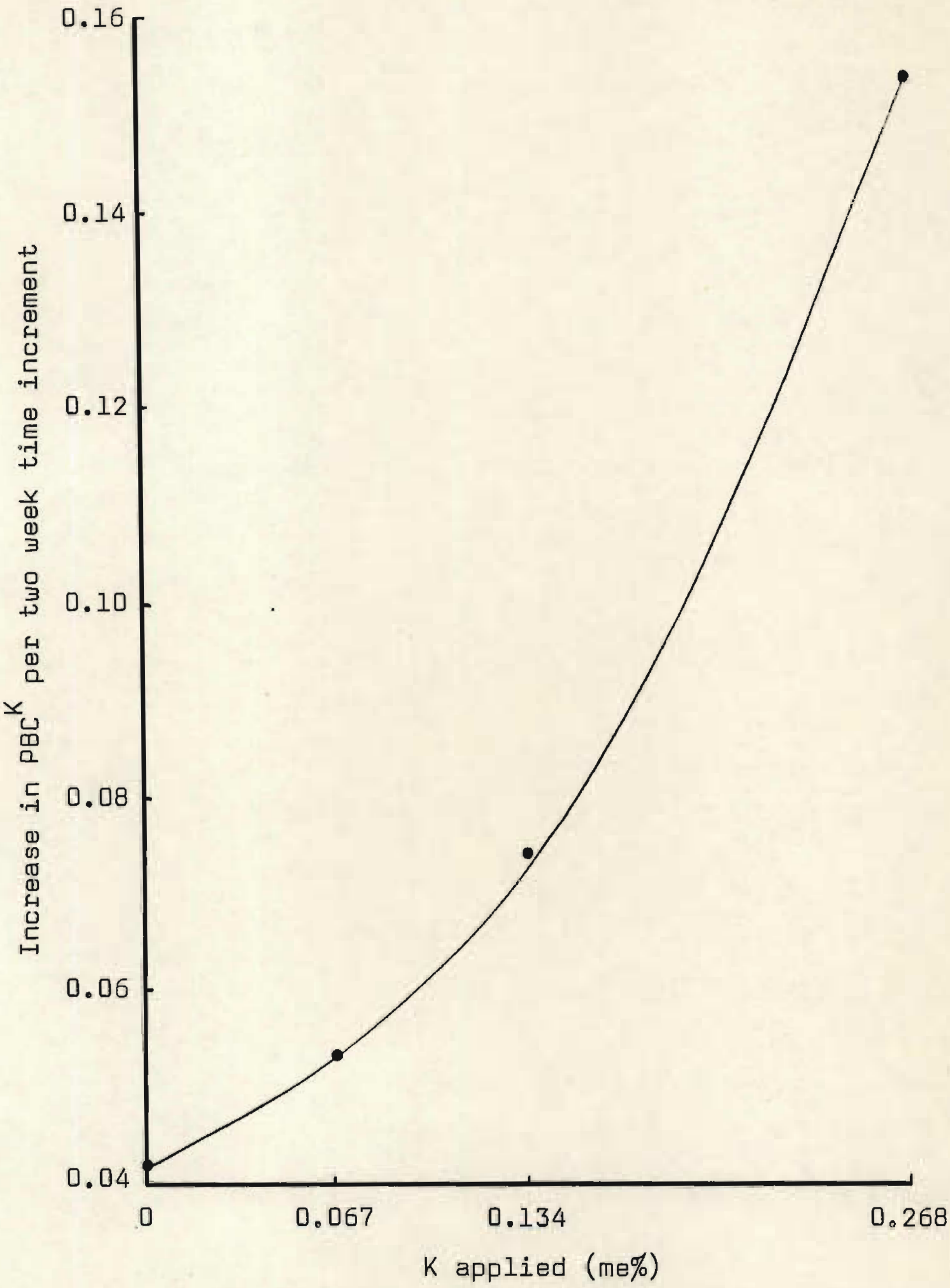


Fig. 9 Average PBC^K increase per two week time increment at four levels of K

drying resulted in an increase in Kex, presumably due to distortion of clay plates and release of K held on edge and intralattice sites (Scott and Smith, 1968). Such release would result in an at least concomitant increase in C.E.C., which would, in turn, due to the enhanced adsorption of Ca, lead to changes in AR_o^K and PBC^K similar to those observed (Beckett, 1964b; Le Roux, 1966; Beckett and Nafady, 1967b). $-\Delta K^o$ was influenced by a significant K level x soil pretreatment interaction, however, drying leading to some increase in $-\Delta K^o$ at low levels of K saturation and to significant ($P = 0.01$) fixation at the highest level of K saturation (fig. 8b). At high K saturation, equilibrium between specifically held K and labile K appears to have been re-established, on the exposure of sites not previously occupied by K, by transfer of some labile K to a more firmly held state. The concomitant decrease in the activity of K would then have similarly affected AR_o^K (fig. 8c). Had air drying lead to an increase in planar sites only, the decrease in AR_o^K would not have been accompanied by a decrease in $-\Delta K^o$. It seems probable that AR_o^K was reduced by both an increase in specific adsorption of K and an increase in the extent of planar surfaces.

CONCLUSIONS

While data reported here do not support the generally accepted hypothesis, that the form of the Q/I relationship is a characteristic soil property (Beckett et al., 1966; Le Roux, 1966; Beckett and Nafady, 1967a; Moss, 1967), they are not without precedent. Small PBC^K changes have previously been noted on K fertilization, storage, exhaustive cropping, and air drying (Matthews and Beckett, 1962; Beckett et al., 1966; Le Roux, 1966; Beckett and Nafady, 1967a; Le Roux and Sumner, 1968a). Few experiments have been designed to test the significance of PBC^K changes statistically, however, and such changes as have been observed have generally been considered negligible and within the limits of experimental error. Furthermore, in most been examined simultaneously and general rather than specific differences have been sought.

If soil tests involving Q/I parameters are to have any practical value the form of the Q/I relationship must remain unchanged by release or fixation of K. In many soils this requirement is apparently fulfilled (Beckett et al., 1966; Beckett and Nafady, 1967a; Moss, 1967) and it could reasonably be argued, that notwithstanding the statistical significance of PBC^K changes observed in this work, such changes were of insufficient magnitude to be practically meaningful. Previous work has shown this not to be the case, however (chapter 3). In both pot and field experimentation marked reductions in the prognostic value of soil tests were attributable to PBC^K changes similar to those observed in this study.

GENERAL DISCUSSION AND CONCLUSIONS

In introducing this dissertation it was suggested that the usefulness of correlative work, designed to establish threshold values for a specific element and crop, is ultimately dependent upon a sound knowledge of the more important soil-plant relationships in that particular system and the efficacy of the soil test used. These investigations have, it is hoped, provided some useful information with regard to the establishment of critical soil K levels for maize production on the sandy hydromorphic soils of Natal.

Although the hydromorphic nature of these soils largely eliminates any danger of K loss to zones beyond the rooting depth of maize, poor retention of potassium by the A horizon is a problem of considerable agronomic significance to both the farmer and fertility specialist. The farmer is faced with the dual problem of maintaining an adequate level of K in the topsoil during early growth and of avoiding economic losses due to luxury consumption, while the fertility advisor is forced to take cognisance of subsoil K.

In present practice farmers can minimise risk of early deficiencies or luxury consumption, by applying K as close as possible to planting, only applying sufficient for crop requirements, optimum fertilization with N and P and endeavouring to maintain the organic matter content of their soils at a high level. A final solution to the problem, however, must depend mainly upon the local production, by industry, of less soluble K fertilizers.

Fertility advisers will have to alter their present soil sampling techniques. Forty-five cm soil cores are as easily obtainable as the presently used, but largely valueless 15cm cores and will considerably improve any assessment of plant available K. Ideally, there should be an assessment of early seasonal requirements based on a 15cm soil core and an evaluation of the total requirements based on a 45cm or even deeper soil core. Work is presently in progress to establish the optimum depth of such samples.

"Unless an approach..... capable of universal application, is fertilizer trials designed for correlation with an ever increasing number of hit-or-miss extractions....." (Nye, 1963). That this statement is in essence true cannot be disputed and the benefits resulting from development of some universal procedure would be inestimable. Need for many years of painfully tedious empirical calibration work would be obviated and agriculturally more backward countries would be able to make extremely rapid progress with regard to soil fertility expertise. That such a method will evolve sufficiently rapidly to meet the demands of a burgeoning world population is, however, questionable. Ironically one of the major obstacles to the rapid development of revolutionary techniques in this field is that technically advanced countries, those best suited and equipped to conduct such work, are also those which least require it. In such countries soil calibration has developed, through the accumulation of vast masses of empirical data, to the stage where satisfactory fertilizer advice can be given to localised areas. Most of the less developed countries, however, have not had the opportunity to gather such information. Indeed, many still do not possess the personnel or facilities required for such work on a sufficiently localised scale. Unfortunately it is by and large these countries which most urgently need to develop their agricultural capability.

At the time Nye's statement was made it was considered likely that nutrient potential might provide the key to universality, ideas proposed by Schofield (1955) and Woodruff (1955) having provided the basis for suitable analytical techniques. The various techniques based on these concepts have, however, not been widely adopted. Barrow (1967) has suggested that two reasons for this may be the difficulty in measuring the parameters concerned and the view held by early workers that potential alone might be sufficient. Recent findings, however, indicate that even joint consideration of quantity and intensity parameters does not produce any marked improvement in the prognosis of fertility requirements (Barrow, 1966; Zandstra and MacKenzie, 1968). The data presented in this thesis, in fact, tend rather to suggest that from the fact that estimates of K availability obtained in topsoil samples using both the Q/I technique and extraction with neutral N NH_4OAc were not significantly different, Q/I parameters provided somewhat poorer indices when subsoil samples were considered simultaneously. Thus, the requirement that any analytical procedure designed to reduce empiricism should provide fertility indices less affected by soil differences than the commonly used extractions employing normalised electrolytes was not satisfied.

Reasons for this are perhaps to be found in certain weaknesses inherent in the Q/I approach. To have any practical value the relationship between pool of labile K and the equilibrium activity ratio, within a particular soil, must remain unchanged by K release/ fixation phenomena. In other words, the slope of the linear portion of the Q/I curve must be constant. While this is commonly held to be the case (Beckett, 1964b; Beckett et al., 1966; Beckett and Nafady, 1967a; Moss, 1967), evidence presented in this study suggests that this is not necessarily so and that changes in the Q/I relationship may be of sufficient magnitude to have practical significance. In addition, the basic premise of all present techniques involving potential measurements, that the ratio $a_K/\sqrt{a_{Ca} + a_{Mg}}$ in the soil solution has physiological significance, is questionable. Findings presented both here and in the literature (Peech and Bradfield, 1943; Viets, 1944; Van Itallie, 1938, 1948; York et al., 1953; Jacobson et al., 1960; Waisel, 1963) indicate that metabolic processes exert an overriding influence on the cationic suite adsorbed by plants and that it is not solely determined by the compliment of ions adsorbed on root surfaces. The necessity to simultaneously consider both metabolic and pure physico-chemical systems is, in fact, probably one of the major obstacles confronting workers in the field of soil fertility.

In conclusion, it is perhaps pertinent to suggest that soil extractions involving the use of NH_4^+ salts have a sounder theoretical basis than is generally conceded. The similar ionic radii of K^+, NH_4^+, and H_3O^+ ions make the NH_4^+ ion a theoretically suitable substitute for biological significance.

ACKNOWLEDGEMENTS

The writer wishes to thank:

Prof. S.A. Hulme, formerly head of the Department of Crop Science at the University of Natal, now Chief Director (Crops and Pastures) in the Department of Agricultural Technical Services, for making this work possible;

Prof. E.H. Graven, formerly senior lecturer in the Department of Crop Science at the University of Natal, now head of the Department of Crop Science at the University College of Fort Hare, for helpful criticism, advice and encouragement;

Mr. R. Ludorf, Chief Regional Soil Scientist, for his continual support;

Prof. A. Rayner, head of the Department of Biometry at the University of Natal and Dr. R. Pringle, Regional Biometrician, for their very valuable advice and assistance;

Dr. M.E. Sumner, Associate Professor in the Department of Soil Science at the University of Natal for accepting the responsibilities of co-supervision at such a late stage in the work;

and the Department of Agricultural Technical Services for permission to use the results of research projects for thesis purposes.

LITERATURE CITED

ACQUAYE, D.K., MACLEAN, A.J., and RICE, H.M. 1967. Potential and capacity of potassium in some representative soils of Ghana. Soil Sci. 103, 79-89.

ARNOLD, P.W. 1962a. The potassium status of some English soils considered as a problem of energy relationships. Proc. Fert. Soc. 72, 25-55.

ARNOLD, P.W. 1962b. Soil potassium and its availability to plants. Outlook Agric. 3, 263-267.

ARNOLD, P.W., and CLOSE, B.M. 1961. Release of non-exchangeable potassium from some British soils cropped in the glasshouse. J. Agric. Sci. 57, 295-304.

ATTOE, O.J. 1947. Potassium fixation and release in soils occurring under moist and drying conditions. Soil Sci. Soc. Amer. Proc. 11, 145-149.

ATTOE, O.J., and TRUOG, E. 1946. Exchangeable and acid-soluble potassium as regards availability and reciprocal relationships. Soil Sci. Soc. Amer. Proc. 10, 81-86.

AYRES, A.S. and HAGIHARA, H.H. 1953. Effect of the anion on the sorption of potassium by some humic and hydrol humic latosols. Soil Sci. 75, 1-17.

BARBER, S.A. 1968. Mechanism of potassium absorption by plants. p. 293-303. In V.J. Kilmer, S.E. Younts and N.C. Brady (ed). The Role of Potassium in Agriculture. Amer. Soc. of Agron. Madison, Wisonsin.

BARRIE, J.W. 1968. Root distribution and potassium uptake. Fertilité 32, 37-43.

BARROW, N.J. 1966. Nutrient potential and capacity II. Relationship between potassium potential and buffering capacity and the supply of potassium to plants. Aust. J. Agric. Res. 17, 849-861.

BARROW, N.J. 1967. Rapid measurement of potassium potential and buffering capacity and their relation to the supply of potassium to plants. Potash Review. Subject 5, 28th suite.

BARROW, N.J., OZANNE, P.G., and SHAW, T.C. 1965. Nutrient potential and capacity I. The concepts of nutrient potential and capacity and their application to soil potassium and phosphorus. Aust. J. Agric. Res. 16, 61-76.

BECKETT, P.H.T. 1964a. Studies on soil potassium I. Confirmation of the ratio law: Measurement of potassium potential. J. Soil Sci. 15, 1-8.

BECKETT, P.H.T. 1964b. Studies on soil potassium II. The 'immediate' Q/I relations of labile potassium in the soil. J. Soil Sci. 15, 9-23.

BECKETT, P.H.T. 1964c. Potassium - calcium exchange equilibria in soils: Specific adsorption sites for potassium. Soil Sci. 97, 376-383.

BECKETT, P.H.T., and NAFADY, M.N.M. 1967a. Studies on soil potassium VI. The effect of K-fixation and release on the form of the K: (Ca+Mg) exchange isotherm. J. Soil Sci. 18, 244-262.

BECKETT, P.H.T., and NAFADY, M.N.M. 1967b. Effect of K release and fixation on the io-exchange properties of illite. Soil Sci. 103, 410-416.

BECKETT, P.H.T., CRAIG, J.B., NAFADY, M.N.M., and WATSON, J.P. 1966. Studies on soil potassium V. The stability of Q/I relations. Plant and Soil 25, 435-455.

BOAWN, L.C., NELSON, C.E., VIETS, F.G., and CRAWFORD, C.L. 1960. Nitrogen carrier and nitrogen rate influence on soil properties and nutrient uptake by crops. Washington Agr. Exp. Sta. Bull. 614.

BOYED, G.E., SHUBERT, J., and ADAMSON, A.W. 1947. The exchange adsorption of ions from aqueous solutions by organic zeolites : I. J. Am. Chem. Soc. 69, 2818-2824.

BRAY, R.H. 1944. Soil plant relations I. The quantitative relation of exchangeable potassium to crop yields and to crop response to potash additions. Soil Sci. 58, 305-324.

BRAY, R.H., and DE TURK, E.E. 1939. The release of potassium from non-replaceable forms in Illinois soils. Soil Sci. Soc. Amer. Proc. 3, 101.

COLLANDER, R. 1941. Selective absorption of cations by higher plants. Plant Physiol. 16, 691-720.

CONYERS, E.S. 1966. Release of potassium from soils and clays by plant and chemical extractions and the affect on clay mineral structure. Diss. Abstr. 27, 6, 1669B.

CONYERS, E.S., and McLEAN, E.O. 1969. Plant uptake and chemical extractions for evaluating potassium release characteristics of soils. Soil Sci. Soc. Amer. Proc. 33, 226-230.

DE MUMBRUM, L.E., and HOOVER, C.D. 1958. Potassium release and fixation related to illite and vermiculite as single mixtures and in mixtures. Soil Sci. Soc. Amer. Proc. 22, 222-225.

DRAKE, M., and WHITE, J.M. 1961. Influence of nitrogen on uptake of calcium. Soil Sci. 91, 66-69.

DUTHION, C. 1968. Potassium in the soil. Potash Review. Subject 4, 43rd suite.

FAWZY, H., OVERSTREET, R., and JACOBSON, L. 1964. The influence of hydrogen ion concentration on cation absorption by barley roots. Plant Physiol. 29, 234-237.

FEHRENBACHER, J.B., and RUST, R.H. 1956. Corn-root penetration in soils derived from various textures of Wisconsin-age glacial till. Soil Sci. 82, 369-378.

FEIGENBAUM, S., and HAGIN, J. 1967. Evaluation of methods for determining available soil potassium based on potassium uptake by plants. J. Soil Sci. 18, 197-203.

FRANKLIN, R.E. 1966. Exchange and adsorption of cations by excised roots. Soil Sci. Soc. Amer. Proc. 30, 177-181.

FRAPS, G.S. 1929. Relation of water-soluble potash, the replaceable potash and acid soluble potash to the potash removed by crops in pot experiments. Tex. Agr. Sta. Bull. 391.

HAAGSMA, T., and MILLER, M.H. 1963. The release of non-exchangeable soil potassium to cation exchange resins as influenced by temperature, moisture and exchanging ion. Soil Sci. Soc. Amer. Proc. 27, 153-156.

HAGIN, J., and DOVRAT, A. 1963. Note on methods for determination of available soil potassium. Emp. J. Exp. Agric. 31, 186-188.

HANWAY, J.J. 1962. Corn growth and composition in relation to soil fertility II. Uptake of N, P and K and their distribution in different plant parts during the growing

HOGG, D.E., and COOPER, M. 1964. Laboratory studies on losses of P, S and K from Te Kopuru sand. N.Z.J. Agric. Res. 7, 364-374.

HUMPHRIES, A.W., and BAILEY, E.T. 1961. Root weight profiles of eight species of Trifolium grown in swards. Aust. J. Exp. Agric. Husb. 1, 150-152.

JACKSON, W.A., and THOMAS, G.W. 1960. Effects of KCl and dolomitic limestone on growth and ion uptake of the sweet potato. Soil Sci. 89, 347-352.

JACOBSON, L., MOORE, D.P., and HANNAPEL, R.J. 1960. Rôle of calcium in absorption of monovalent cations. Plant Physiol. 35, 352-258.

JAKOBSEN, S.T. 1966. Pot-culture experiments measuring the effects of compound or straight N, P, and K fertilizers on yield, uptake and utilization of added N, P and K. p 393-399. In G.V. Jacks (ed) Soil Chemistry and Fertility. University press, Aberdeen.

KIRBY, E.A., and MENGEL, K. 1967. Ionic balance in different tissues of the tomato plant in relation to nitrate, urea or ammonium nutrition. Plant Physiol. 42, 6-14.

KOCH, J.T. 1968. Assessing the potassium status of soils. M.Sc. Thesis, University of Natal.

KÖHNLEIN, J., OEHRING, M., and SPIELHAUS, G. 1966. Nahrstoffauswaschung aus der Acherkrume von sechs Schleswig-Holsteinischen Böden in den Unterboden. Z. Acher - u Pfl. Bau. 124, 212-233.

LAWS, W.D. 1962. Potassium status of eight Texas soils as related to crop yield and plant composition. Soil Sci. 94, 230-234.

LEUBS, R.E., STANFORD, G., and SCOTT, A.D. 1956. Relation of available potassium to soil moisture. Soil Sci. Soc. Amer. Proc. 20, 45-50.

LE ROUX, J. 1966. Studies of ionic equilibria in Natal soils. Ph.D. Thesis, University of Natal.

LE ROUX, J., and SUMNER, M.E. 1968a. Labile potassium in Soils I. Factors affecting the quantity - intensity (Q/I) parameters. Soil Sci. 106, 35-41.

LE ROUX, J. and SUMNER, M.E. 1968b. Labile potassium in soils II.

LUTERICK, M.C. 1963. The effect of lime and phosphate on the downward movement of potassium in Red Bay fine sandy loam. Soil Crop Sci. Soc. Fla. Proc. 23, 90-94.

MACLEAN, A.J. 1960. Water-soluble K, percent K-saturation, and pK-$\frac{1}{2}$p (Ca+Mg) as indices of management effect on K status of soils. Int. Congr. Soil Sci. Trans. 7th (Madison, Wis.) 3, 86-91.

MATTHEWS, B.C., and BECKETT, P.H.T. 1962. A new procedure for studying the release and fixation of K ions in soil. J. Agr. Sci. 58, 59-64.

MATTHEWS, B.C., and SHERELL, C.G. 1960. Effect of drying on exchangeable potassium of Ontario soils and the relation of exchangeable potassium to crop yield. Canad. J. Soil Sci. 40, 35-41.

McEWEN, H.B., and MATTHEWS, B.C. 1958. Rate of release of non-exchangeable potassium by Ontario soils in relation to natural soil characteristics and management practices. Canad. J. Soil Sci. 38, 36-43.

McLEAN, E.O. 1957. Plant growth and uptake of nutrients as influenced by level of nitrogen. Soil Sci. Soc. Amer. Proc. 21, 219-222.

McLEAN, E.O., ADAMS, D., and FRANKLIN, R.E. 1956. Cation exchange capacities of plant roots as related to their nitrogen contents. Soil Sci. Soc. Amer. Proc. 20, 345-347.

MECKLENBURG, R.A., TUCKEY, H.B. Jr., and MORGAN, J.V. 1966. A mechanism for the leaching of calcium from foliage. Plant physiol. 14, 1616-1623.

MEHLICH, A., and REED, J.F. 1945. The influence of degree of saturation, K-level, and calcium additions on removal of K, Ca and Mg. Soil Sci. Soc. Amer. Proc. 10, 87-93.

MORTLAND, M.M. 1958. Kinetics of potassium release from biotite. Soil Sci. Soc. Amer. Proc. 22, 503-508.

MORTLAND, M.M. 1961. The dynamic character of potassium release and fixation. Soil Sci. 91, 11-13.

MOSS, P. 1964. A potassium relationship between soil solution and Cacao bark. Nature 201, 729-730.

MOSS, P. 1967. Independence of soil quantity - intensity relationships to changes in exchangeable potassium. Similar potassium exchange constants for soils within a soil type. Soil Sci. 103, 196-201.

MUNSON, R.D., and NELSON, W.L. 1963. Movement of applied potassium in soils. Jour. of Agric. & Food chem. 11, 193-201.

NELSON, W.L. 1967. Nitrogen, phosphorus and potassium - needs and balance for high yields. p 57-67. In D.A. Rohweder and S.E. Younts (ed.) Maximum Crop Yields - The Challenge. Amer. Soc. of Agron, Madison, Wisconsin.

NELSON, W.L., MEHLICH, A., and WINTERS, E. 1953. The development, evaluation, and use of soil tests for phosphate availability. Am. Soc. Agron. Mono. 4, 153-188.

NYE, P.H. 1963. Soil analysis and the assessment of fertility in tropical soils. J. Sci. Fd. Agric. 14, 277.

NYE, P.H. 1968. Processes in the root environment. J. Soil Sci. 19, 205.

OVERSTREET, R., JACOBSON, L., and HANDLEY, R. 1952. The effect of calcium on the absorption of potassium by barley roots. Plant Physiol. 27, 583-590.

OZANNE, P.G., ASHER, C.J., and KIRTON, D.J. 1965. Root distribution in a deep sand and its relation to the uptake of added potassium by pasture plants. Aust. J. Agric. Res. 16, 785-800.

PATERSON, J.W., and RICHER, A.C. 1966. Effect of longterm applications on exchangeable and acid soluble potassium. Agron. J. 58, 589-591.

PEECH, M., and BRADFIELD, R. 1943. The effect of lime and magnesia on the soil potassium and on the absorption of potassium by plants. Soil Sci. 55, 37-48.

PFAFF, C. 1963. The behaviour of phosphorus and alkalis in soil during long-term lysimeter trials. Z. Acher - u Pfl. Bau 117, 100-113.

PRATT, P.F. 1951. Potassium removal from Iowa soils by greenhouse and laboratory procedures. Soil Sci. 72, 107-117.

PRATT, P.F., and GOULBEN, B. 1957. Potassium fixation in soil of a long-term fertility trial with citrus. Soil Sci. 84, 225-230.

RAMAMOORTHY, B., and PALIWAL, K.V. 1965. Potassium adsorption ratio of some soils in relation to their potassium availability to paddy. Soil Sci. 99, 236-242.

REITEMEIER, R.F., BROWN, J.C., and HOLMES, R.S. 1951. Release of native and fixed non-exchangeable potassium by soils containing hydrous mica. Tech. Bull. U.S. Dept. Agric. 1049.

RICH, C.I. 1964. Effect of cation size and pH on potassium exchange in Nason soil. Soil Sci. 98, 100-106.

SAYRE, J.D. 1948. Mineral accumulation in corn. Plant Physiol. 23, 267-281.

SCHOFIELD, R.K. 1955. Can a precise meaning be given to "available" soil phosphorus. Soils and Tests. 18, 373-375.

SCOTT, A.D., and SMITH, S.J. 1968. Mechanism for soil K release by drying. Soil Sci. Soc. Amer. Proc. 32, 443-444.

SKEEN, J.B. 1968. The measurement of potassium potentials in acid soils. Ph.D. Thesis, University of Natal.

STANTON, D.A. 1958. Evaluation of the potassium-supplying power of some Natal soils. M.Sc. Thesis, University of Natal.

THOMAS, R.P., and SCHUELER, J.E. 1937. Potassium retained in the exchangeable form by some Maryland soils. Agron. J. 29, 17-22.

TINKER, P.B. 1964a. Studies on soil potassium III. Cation activity ratios in acid Nigerian soils. J. Soil Sci. 15, 24-34.

TINKER, P.B. 1964b. Studies on soil potassium IV. Equilibrium cation activity ratios and responses to potassium fertilizer of Nigerian oil palms. J. Soil Sci. 15, 35-41.

TUCKEY, H.B., and TUCKEY, H.B. Jr. 1959. Practical implications of nutrient losses from plant foliage by leaching. Proc. Amer. Soc. Hort. Sci. 74, 671-676.

TUCKEY, H.B. Jr., and TUCKEY, H.B. 1962. The loss of organic and inorganic materials by leaching from leaves and other above-ground plant parts. p 289-302. In Radioisotopes in soil-plant nutrition studies. IAEA, Vienna.

VAN DER EYK, J.J., MacVICAR, C.N., and DE VILLIERS, J.M. 1969. Soils

VAN ITALLIE, Th.B. 1938. Cation equilibria in plants I. Soil Sci. 46, 175-186.

VAN ITALLIE, Th.B. 1948. Cation equilibria in plants in relation to the soil II. Soil Sci. 65, 393-416.

VIETS, F.G. 1944. Calcium and other polyvalent cations as accelerators of ion accumulation by excised barley roots. Plant Physiol. 19, 446-480.

VOLK, N.J. 1940. The effect of soil characteristics and winter legumes on the leaching of potassium below the 8-inch depth in some Alabama soils. J. Am. Soc. Agron. 32, 888-890.

WAISEL, Y. 1962. The effect of Ca on the uptake of monovalent ions by excised barley roots. Phys. Plantarum 15, 709-724.

WEINMANN, H. 1956. Studies on the chemical composition and nutrient uptake of maize. Rhod. Agr. Jour. 53, 168-181.

WIKLANDER, L. 1958. Mineral nutrition of the soil. p 118-169. In Encyclopedia of Plant Physiology. Springer-Verlag. Berlin. Gottingen. Heidelberg.

WOOD, L.K., and DE TURK, E.E. 1942. The release of fixed potassium to replaceable or water soluble forms. Soil Sci. Soc. Amer. Proc. 7, 148.

WOODRUFF, C.M. 1955. The energies of replacement of calcium by potassium in soils. Soil Sci. Soc. Amer. Proc. 19, 167-171.

WOODRUFF, C.M., and McINTOSH, J.L. 1960. Testing soil for potassium. Trans. 7th Int. Congr. Soil Sci. (Madison, Wisconsin) 3, 80-85.

YORK, E.T., BRADFIELD, R., and PEECH, M. 1953. Reciprocal relationship between calcium and potassium in plants. Soil Sci. 76, 481-491.

ZANDSTRA, H.G., and MACKENZIE, A.F. 1968. Potassium exchange equilibria and yield responses of oats, barley and corn on selected Quebec soils. Soil Sci. Soc. Amer. Proc. 32, 76-79.