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# Potassium supplying power of a Typic Ustochrept profile using quantity/intensity technique in a long-term fertilized plot

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## SUMMARY

The effect of 27 years of continuous cropping, fertilization and manuring on potassium (K) supplying capacity of a Typic Ustochrept soil profile from Delhi, India under a maize–wheat–cowpea (fodder) cropping system was investigated by employing the quantity/intensity (Q/I) approach. The predominant mineral suite of the $<2$ μm clay fraction was illite. The values of equilibrium activity ratio of K in solution in equilibrium with the soil ($AR_e^K$), labile pools of K ($K_L$), immediately available K ($\Delta K_0$), K available with difficulty ($K_X$) and water soluble + exchangeable K (1 M $NH_4OAc$ K) in different soil layers (0 to 105 cm) under different treatments were in the following order: 100% nitrogen, phosphorus and potassium (NPK) + farmyard manure (FYM) > 100% NPK > control (no fertilizer) > 100% N > 100% NP. The $AR_e^K$ value, a measure of availability or intensity of labile K in soil decreased with profile depth due to greater K fixation by specific sites in the lower layers. The quantity of specifically sorbed K ($K_X$) and the potential buffering capacity of soil ($PBC^K$) showed a increasing trend with soil depth. In soil without K fertilizer treatments (control, 100% N and 100% NP) about 100% of the total K uptake by crops was from non-exchangeable soil K reserve as compared to 49·5 and 32·2% when annually 84 kg K/ha and 84 kg K/ha + FYM at the rate of 15 t/ha were applied. The results showed the greatest depletion of non-exchangeable K reserves in the plots which did not receive K fertilization. To ensure sustained crop production under intensive cropping, application of recommended dose of NPK plus FYM is required.

## INTRODUCTION

The power of a given soil to supply any particular nutrient is characterized by both the total amount of nutrient present and the energy level or intensity at which it is supplied. Several researchers have used the quantity/intensity (Q/I) technique, which is the relationship between the amount (Q) present and the availability or intensity (I), to assess the status of soil potassium (K) (Beckett 1964; Sparks & Liebhardt 1981; Jimenez & Parra 1991; Hamdan *et al.* 1999). The ability of the soil to maintain a nearly constant K concentration or intensity in the soil solution when this nutrient is either added or removed from the solution is known as the K buffering power. Various interpretations have been made on the parameters that can be derived from a Q/I plot. It has been reported that higher values of labile K indicate a greater K release into soil solution resulting in a larger pool of K (Sparks & Liebhardt 1981). A higher soil potential buffering capacity ($PBC^K$) value is indicative of good K availability while a low $PBC^K$ would suggest a need for K fertilization (Le Roux & Sumner 1968; Sparks & Liebhardt 1981). Traditionally, K availability of Indian soils is studied by its extraction with neutral one molar ammonium acetate (1 M $NH_4OAc$). However, evidence shows that 1 M $NH_4OAc$ K has failed to indicate the changes in soil K that took place under cropping (Velayutham *et al.* 1985). The parameters obtained from the Q/I curves give a more complete information about the soil K status than the concentration of K commonly determined by ammonium acetate (De La Horra *et al.* 1998).

Several studies have investigated the influence of K fertilization strategies on Q/I parameters in soil.

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These studies, however, did not evaluate the long-term effects of cropping, K fertilization and manuring on the Q/I relation in soils. Long-term experiments are an important means for obtaining information on the long-term sustainability of agricultural systems. The classical sites at Rothamsted (Jenkinson 1991) and the Morrow plots at the University of Illinois (Mitchell *et al.* 1991) are typical examples. The long-term field experiment described here was established in 1971. Although a major part of the nutrients are absorbed by crops from the surface soil, subsurface soil contributions are often substantial. Part of the nutrients applied to surface soil may leach down and accumulate in subsurface horizons which are often exploited by the deep-rooted crops in a crop rotation (Sparks *et al.* 1980). A knowledge of Q/I relationship of potassium in soil together with their distribution in the zone of root penetration helps to predict the fate of added K in soil profile as well as nature of K supply from subsoil layers to plant K nutrition particularly in deep rooted crops and in formulating sound fertilizer recommendations. Therefore, the present study was conducted to investigate the effect of long-term cropping, fertilization and manuring on the K supplying power of a Typic Ustochrept profile using the Q/I relationship.

## MATERIALS AND METHODS

### *Experimental details*

A long-term fertilizer experiment at New Delhi, India under the aegis of the All India Co-ordinated Research Project of the Indian Council of Agricultural Research was started in 1971 with *Kharif* (wet season) pearl millet (*Pennisetum typhoides* Burn. f.), *Rabi* (winter season) wheat (*Triticum aestivum* L.) and summer cowpea (fodder) (*Vigna unguiculata*) cropping system on a Typic Ustochrept. Pearl millet was replaced with maize (*Zea mays* L.) in the rotation since 1982. The experimental site is situated at a latitude of 28° N and longitude of 77° E and is about 250 m a.s.l. The soil is a Typic Ustochrept with illite as a dominant mineral. Five out of the ten treatments were selected for this study in the year 1998. All treatments were replicated four times in a randomized block design. All recommended management practices were adopted. The treatments selected for the present study were control, 100% nitrogen (N), 100% nitrogen and phosphorus (NP), 100% nitrogen, phosphorus and potassium (NPK) and 100% NPK + farmyard manure (FYM). Nutrients N, P and K were applied at N: 120 kg/ha, P: 26 kg/ha and K: 33 kg/ha each to pearl millet/maize and wheat crops and N: 20 kg/ha, P: 17 kg/ha and K: 17 kg/ha to cowpea (fodder). Farmyard manure (FYM) was applied every year only to *Kharif* pearl millet/maize at 15 t/ha (N 0·65%, P 0·14%, K 0·42%). The sources of N, P and K were urea, diammonium phosphate and muriate of potash, respectively. The full details of experiments have been described earlier (Singh *et al.* 1998).

Table 1. *Initial soil characteristics of the experimental plot*

| Soil properties | Depth (0–15 cm) |
|---|---|
| pH (1:2·5 $H_2O$) | 8·0 |
| EC (dS/m) | 0·45 |
| $CaCO_3$ (g/kg) | 8·5 |
| Organic carbon (g/kg) | 4·4 |
| Water soluble + exchangeable K ($cmol_c$/kg) | 0·177 |
| Total K (g/kg) | 14·5 |
| CEC [$cmol(p^+)$/kg] | 10·6 |
| Taxonomic classification | Typic Ustochrept |
| Texture | Sandy loam |
| Sand (g/kg) | 690 |
| Silt (g/kg) | 160 |
| Clay (g/kg) | 140 |
| $Illite_{1*}$ | |
| $Kaolinite_2$ | |
| $Vermiculite_3$ | |
| $Mica\text{-}chlorite_3$ | |
| $Mica\text{-}smectite_4$ | |

*$_1$ Represents the clay mineral found in the higher quantity.

### *Soil analyses*

Soil samples were taken at seven depth increments (0 to 15, 15 to 30, 30 to 45, 45 to 60, 60 to 75, 75 to 90 and 90 to 105 cm) using a tube auger from four replicates of each treated plot after 27 cycles of crop rotation. The soil samples were air dried and passed through a 2 mm sieve. The replicated samples were pooled, thoroughly mixed and a composite soil sample of each treated plot for different depths was prepared for quantity/intensity (Q/I) study. Initial soil samples collected at the start of the experiment (1971) were analysed for physicochemical characteristics (Table 1). Soil pH and electrical conductivity (EC) were measured in a 1:2·5 (w/v) soil/water suspension (Jackson 1973). The samples were prepared for soil mineral particle size fractionation by treatment with 30% $H_2O_2$ to remove organic matter (Kunze 1965) and the Na-dithionite-citrate-bicarbonate to remove Fe-oxides (Mehra & Jackson 1960). Sand was separated from silt and clay by wet sieving and clay was separated from silt by repeated centrifugation and decantation. X-ray diffraction was performed on the clay fraction of the soils (Rich & Barnhisel 1977). Organic carbon (organic C) was determined by the wet oxidation method of Walkley & Black (1934), calcium carbonate ($CaCO_3$) was estimated using the method of Bundy & Bremner (1972), and cation

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exchange capacity (CEC) of the soils by the sodium acetate ($NaC_2H_3O_2$) method (United States Soil Salinity Laboratory 1954). Water soluble + exchangeable potassium extracted in 1 M ammonium acetate ($NH_4OAc$) (Hanway & Heidel 1952) was measured by Elico flame photometer. Total K was determined by digesting the soil samples using hydrofluoric acid (HF) and perchloric acid ($HClO_4$) (Pratt 1965). The dry matter yields of grain and straw and K contents in the respective plant parts were used for computing total plant K uptake.

### *Quantity/intensity relationships*

For quantity/intensity (Q/I) studies replicated soil samples collected after 27 years from maize–wheat–cowpea fodder cropping system was used. The Q/I relationship of soil K was determined by equilibrating 2 g soil in duplicate with 20 ml of 0·01 M calcium chloride ($CaCl_2$) containing 0, 40, 80, 120, 160 and 200 mg K/kg soil from KCl, and with 0·01 M $CaCl_2$ containing no K at soil : solution ratios varying from 1 : 10 to 1 : 200. The soil and solution mixture was shaken for 2 h, allowed to stand overnight at 25 ± 1 °C. The samples were centrifuged at 1500 rpm for 5 min, and the filtered supernatant solutions were analysed for K by flame photometry and calcium (Ca) + magnesium (Mg) by titration with 0·01 N EDTA (Vogel 1978).

The potassium intensity factor ($AR^K$) was computed from the measured concentrations of Ca, Mg and K in the supernatant solution after equilibration and activity coefficients determined according to the Debye–Huckel theory as follows from equation 1 through equation 3 (Moore 1972):

$$\log \sigma \pm = \frac{-az^+z^-\sqrt{I}}{1+\alpha\beta\sqrt{I}} \qquad (1)$$

where
$\sigma \pm$ = the mean activity coefficient of the electrolyte
a = constant (0·5042)
$z^+$ = valency of cation
$z^-$ = valency of anion
$\alpha\beta$ = assumed to be 1, and
$I$ = ionic strength.
Where

$$I = \tfrac{1}{2}\Sigma_i C_i z_i^2 \qquad (2)$$

and where
$C_i$ = concentration of ion i and
$z_i$ = valency of ion i.
The activity ratio ($AR^K$) was calculated as

$$AR^K = \frac{C_K({}_\sigma KCl)^2}{\sqrt{C_{Ca}+C_{Mg}}({}_\sigma CaCl_2)^{3/2}} \qquad (3)$$

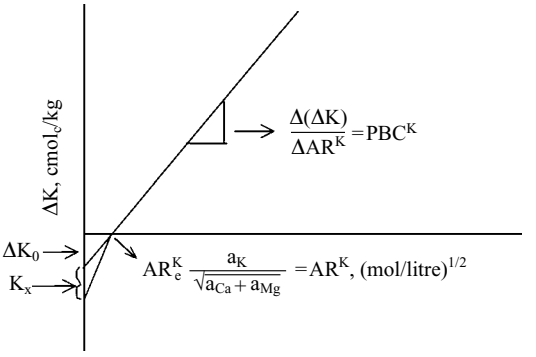



Fig. 1. A typical quantity/intensity (Q/I) plot.

where
$C_{Ca}$, $C_K$, $C_{Mg}$ = equilibrium concentrations of Ca, K, and Mg
${}_\sigma KCl$ = activity coefficient of KCl, and
${}_\sigma CaCl_2$ = activity coefficient of $CaCl_2$.
The quantity (Q) by which the soil gained or lost $K^+$ in reaching equilibrium, $\pm\Delta K$ was obtained by subtracting the concentrations of the solution before and after equilibration. A typical Q/I curve is shown in Fig. 1. A Q/I plot of $\Delta K$ on the ordinate axis and $AR^K$ on the abscissa axis was constructed for each sample from which values for equilibrium activity ratio ($AR^K_e$), K held at non-specific sites ($\Delta K_0$), K held at specific sites ($K_x$) and potential buffering capacity ($PBC^K$) were determined as explained below. The $AR^K_e$ was obtained from the intersection of the Q/I curve with the $\Delta K = 0$ axis. Potassium held at non-specific sites ($\Delta K_0$) was determined by extending the linear part of the curve to $AR^K = 0$ point. Potassium held at specific sites ($K_x$) was assumed to be difference between the intercepts of the linear and curved part of the zero activity ratio. The potential buffering capacity was calculated as the slope of the linear section of the Q/I curve.

## RESULTS AND DISCUSSION

### *Quantity/intensity (Q/I) relation parameters of soil potassium*

#### *Equilibrium activity ratio ($AR^K_e$)*

The values of Q/I parameters of potassium for various treatments after 27 years of cropping, fertilization and manuring are given in Table 2. Cropping with and without potassium fertilization showed higher variability in equilibrium activity ratio ($AR^K_e$). The $AR^K_e$ value, measure of availability or intensity of labile K in soil was higher in 100% NPK + FYM treatment, followed by 100% NPK, control (no fertilizer), 100% N and 100% NP. Plots which received K fertilization showed higher values of $AR^K_e$

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Table 2. *Quantity/intensity parameters in the profile at the end of 27 cycles of maize–wheat–cowpea (fodder) crop rotation under different fertilizer treatment combinations*

| Treatment | Depth (cm) | $AR_e^K$ $(mol/litre)^{1/2} \times 10^{-3}$ | $-\Delta K_O$ | $K_X$ | $K_L$ | $PBC^K$ $cmol_c/kg \times (mol/litre)^{-1/2}$ |
|---|---|---|---|---|---|---|
| | | | $(cmol_c/kg)$ | | | |
| Control | 0–15 | 2·36 | 0·16 | 0·17 | 0·33 | 22·7 |
| | 15–30 | 1·80 | 0·10 | 0·12 | 0·22 | 26·3 |
| | 30–45 | 1·44 | 0·03 | 0·13 | 0·16 | 38·1 |
| | 45–60 | 1·05 | 0·02 | 0·13 | 0·15 | 40·0 |
| | 60–75 | 1·26 | 0·07 | 0·16 | 0·23 | 45·6 |
| | 75–90 | 1·39 | 0·07 | 0·20 | 0·27 | 48·7 |
| | 90–105 | 1·63 | 0·08 | 0·22 | 0·30 | 52·6 |
| 100 % N | 0–15 | 1·08 | 0·07 | 0·19 | 0·26 | 26·5 |
| | 15–30 | 0·74 | 0·11 | 0·12 | 0·23 | 32·2 |
| | 30–45 | 0·72 | 0·08 | 0·13 | 0·21 | 34·1 |
| | 45–60 | 0·42 | 0·05 | 0·14 | 0·19 | 39·2 |
| | 60–75 | 0·55 | 0·06 | 0·16 | 0·22 | 45·4 |
| | 75–90 | 0·69 | 0·06 | 0·18 | 0·24 | 48·5 |
| | 90–105 | 0·77 | 0·08 | 0·18 | 0·26 | 52·0 |
| 100 % NP | 0–15 | 0·59 | 0·09 | 0·17 | 0·26 | 27·3 |
| | 15–30 | 0·39 | 0·12 | 0·10 | 0·22 | 38·7 |
| | 30–45 | 0·37 | 0·04 | 0·16 | 0·20 | 43·6 |
| | 45–60 | 0·34 | 0·02 | 0·17 | 0·19 | 49·7 |
| | 60–75 | 0·41 | 0·02 | 0·19 | 0·21 | 53·6 |
| | 75–90 | 0·50 | 0·02 | 0·20 | 0·22 | 59·2 |
| | 90–105 | 0·64 | 0·03 | 0·21 | 0·24 | 60·1 |
| 100 % NPK | 0–15 | 4·26 | 0·17 | 0·20 | 0·37 | 16·7 |
| | 15–30 | 1·63 | 0·12 | 0·15 | 0·27 | 25·3 |
| | 30–45 | 0·82 | 0·10 | 0·13 | 0·23 | 29·4 |
| | 45–60 | 0·64 | 0·04 | 0·14 | 0·19 | 38·9 |
| | 60–75 | 0·66 | 0·03 | 0·17 | 0·20 | 42·0 |
| | 75–90 | 1·47 | 0·09 | 0·24 | 0·33 | 48·6 |
| | 90–105 | 2·25 | 0·12 | 0·26 | 0·38 | 51·7 |
| 100 % NPK + FYM | 0–15 | 5·63 | 0·23 | 0·30 | 0·53 | 20·0 |
| | 15–30 | 3·87 | 0·14 | 0·32 | 0·46 | 32·6 |
| | 30–45 | 1·76 | 0·10 | 0·35 | 0·45 | 40·0 |
| | 45–60 | 1·46 | 0·06 | 0·37 | 0·43 | 41·3 |
| | 60–75 | 1·75 | 0·07 | 0·37 | 0·44 | 45·7 |
| | 75–90 | 2·09 | 0·09 | 0·38 | 0·47 | 56·2 |
| | 90–105 | 2·94 | 0·11 | 0·40 | 0·51 | 68·2 |

which confirmed with findings of many workers (Le Roux & Sumner 1968; Sparks & Liebhardt 1981; De La Horra *et al.* 1998). Among the treatments, the lowest $AR_e^K$ was recorded in the 100 % NP treatment which is attributed to the largest depletion in soil K. This was evident from the total K uptake pattern of crops during 27 year crop cycles. It was 3070 kg K/ha in 100 % N treatment and 3080 kg K/ha in 100 % NP treatment, compared with 1747 kg K/ha in control plots (Table 3). The values of $AR_e^K$ in 100 % NP treatment in the surface soil (0–15 cm) was about 7·2 and 9·5 times lower than NPK and NPK + FYM treated plots, respectively. The $AR_e^K$ values ranged from 0·59 to 5·63 $(mol/litre)^{1/2} \times 10^{-3}$ and from 0·34 to 3·87 $(mol/litre)^{1/2} \times 10^{-3}$ in the surface and subsoils, respectively, in all the treatments. The $AR_e^K$ values showed a decreasing trend up to a depth of 60 cm and thereafter increased in 60–105 cm soil layer in all the plots. The decreased $AR_e^K$ values with increasing depth might be attributed to the dominantly illitic nature of the clay in these soils. It is well known that illite prevents the persistence of high levels of potassium in soil solution because of the specificity of wedge shaped zones at its frayed edges for this element which is expected to cause lower values with increasing depth. Hamdan *et al.* (1999) indicated that the values of $AR_e^K$ showed a decreasing trend with depth. The $AR_e^K$ values throughout the profile suggest that the bulk of soil K was preferentially held at edge positions of the clay crystals since the $AR_e^K$ values were $< 0{\cdot}006$ $(mol/litre)^{1/2}$. Schouwenburg & Schuffelen (1963) theorized that if $AR_e^K$ was $< 0{\cdot}001$, the

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Table 3. *Removal and addition of potassium and grain yield* during 27 crop cycles of maize–wheat–cowpea rotations*

| Treatment | Fertilizer K added during 27 crop rotations | 1 M $NH_4OAc$ K (kg/ha) (0–15 cm) | | Total K removal | Contribution of non-exch. K (kg/ha) | % contribution | Maize grain yield (t/ha) | Wheat grain yield (t/ha) |
|---|---|---|---|---|---|---|---|---|
| | | Before cropping (1971) | After cropping (1998) | | | | | |
| Control | 0 | 155 | 180·3 | 1747 | 1772 | 101·4 | 1·02 | 2·36 |
| 100 % N | 0 | 155 | 172·6 | 3070 | 3088 | 100·6 | 1·58 | 4·12 |
| 100 % NP | 0 | 155 | 165·9 | 3080 | 3091 | 100·3 | 1·73 | 4·18 |
| 100 % NPK | 2260 | 155 | 238·2 | 4279 | 2102 | 49·1 | 1·98 | 4·49 |
| 100 % NPK + FYM | 3952 | 155 | 260·9 | 5643 | 1797 | 31·8 | 2·70 | 4·72 |
| S.E. | — | — | — | — | — | — | 0·61 | 0·93 |
| D.F. | — | — | — | — | — | — | 12 | 12 |

* Grain yield in 1997–98.

adsorbed K was at edge positions, and if > 0·01 (mol/litre)$^{1/2}$, K was adsorbed at planar positions.

### *Labile pool of K ($K_L$)*

The labile pool ($K_L$) of K represents the amount of K which is capable of ion exchange during the period of equilibration between soil solids and soil solution. This is comprised of two distinct components, the non-specifically held or immediately available K ($\Delta K_0$) and specifically held or not immediately available K ($K_x$). The labile pool of potassium ($K_L$) in different treatments in the surface soil ranged from 0·26 to 0·53 $cmol_c$/kg. The highest and lowest values of $K_L$ were observed in NPK + FYM and NP plots, respectively. It has also been reported that addition of inorganic K or organic material will keep the concentration of exchangeable K at higher level (Tuivavalagi *et al.* 1996). The 1 M $NH_4OAc$ K and $K_L$ values of these plots were also higher than the control, N and NP plots throughout the profile of this soil. In all the treatments, surface soils (0–15 cm) showed the highest $K_L$ values. The labile pool of K in all treatments decreased from 0–15 to 15–60 cm soil depth and thereafter increased slightly. These decreases can be ascribed to crop removal, transformation of K to non-exchangeable forms or, in this soil, possible leaching out of the soil profile (Bertsch & Thomas, 1985). The relatively higher content of labile pools of K in the 90–105 cm soil layer in all treatments suggests the downward movement of K through the soil profile and would tend to accumulate in the lower layer by virtue of light texture of the soils. In general, soils with high $K_L$ values showed higher $AR_e^K$. Total labile K values were slightly higher than the 1 M $NH_4OAc$ K. The $K_L$ values followed the same trend as 1 M $NH_4OAc$ K throughout the profile (Table 2 and Fig. 2).

### *Non-specific K or immediate available K ($-\Delta K_0$)*

The quantity of K that is held on non-specific sites ($\Delta K_0$) ranged from 0·085 to 0·23 $cmol_c$/kg which constituted 33·3 to 43·4 % of the labile pool ($K_L$). Plots without K fertilizer showed a decreasing trend in $\Delta K_0$ values in both surface and subsoils compared to K treated plots. From all the depths 100 % NPK + FYM followed by 100 % NPK treated plots showed larger $\Delta K_0$ values. The lowest $\Delta K_0$ value was observed in case of 100 % NP plots. It seems plausible that application of optimum dose of fertilizer N and P in 100 % NP treated plot caused more depletion of soil K from interlayer positions associated with the phenomenon of accumulation of greater amounts of $NH_4^+$ due to hydrolysis of urea. Under such a situation $NH_4^+$ going inside the interlayer positions will be adsorbed on the preferentially higher bonding energy

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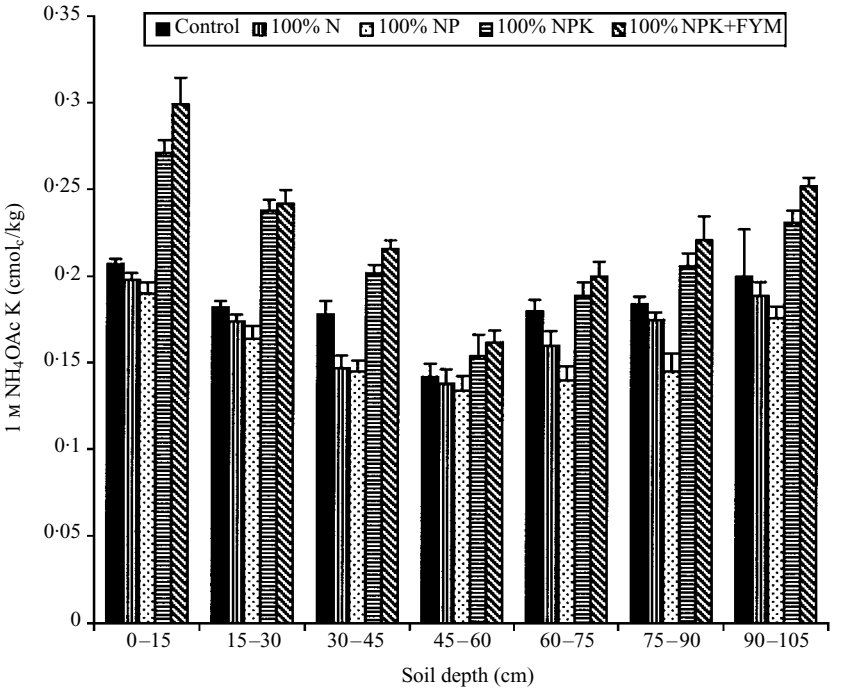



Fig. 2. Water soluble + exchangeable K (1 M $NH_4OAc$) distribution at different soil layers of a profile under different treatments after 27 years of cropping. Vertical bars represent the standard errors of the difference.

sites. That the $NH_4^+$ accumulated in the soil could be fixed in the interlayer sites of the adsorption complex and there was difficulty in replacing this $NH_4^+$ by $K^+$, was observed by Welch & Scott (1960). In K treated plots, $\Delta K_0$ became more negative and there was greater release of K into soil solution, resulting in a larger pool of labile K. The $\Delta K_0$ tended to become less negative with increasing depth. This further indicated that the Ustochrept subsoil had a strong ability to adsorb K. Le Roux (1966) noted that $\Delta K_0$ is a better estimate of soil labile K than normal exchangeable K. The $\Delta K_0$ values obtained in all the treatments were well below the amount of 1 M $NH_4OAc$ K in soil. This supports the findings of Beckett & Nafady (1967) that a part of exchangeable K does not contribute to $\Delta K_0$ value. The $\Delta K_0$ followed almost the same trend as 1 M $NH_4OAc$ K in the profile.

*Specific K or not immediately available K ($K_x$)*

The quantity of K that is held at specific sites ($K_x$) in the surface soil ranged from 0·15 to 0·30 $cmol_c$/kg which constituted 52–74% of the labile pool ($K_L$). In all the treatments the value of $K_x$ was much higher than $\Delta K_0$ which implied that the labile pool of K was mainly controlled by specific K. Maximum values of $K_x$ was observed in 100% NPK + FYM plots. Lower $K_x$ values in 100% NP followed by 100% N could be due to constant removal of K from soil reserve source under intensive cropping. The $K_x$ values showed a increasing trend with depth. This strongly suggests that there were more specific sites for K in the subsoils. Moreover the dominant mineral in this soil is illite which contain wedge zones or specific sites for K adsorption. Ammonium, with a crystalline radius of 1·43 A° could displace $K^+$ with a crystalline radius of 1·33 A° from these specific sites, resulting in higher water soluble + exchangeable K with $NH_4OAc$ (Rich 1964). Therefore, in soils of this type, 1 M $NH_4OAc$ would tend to over-predict water soluble + exchangeable K.

*Potential buffering capacity ($PBC^K$)*

The potential buffering capacity of K ($PBC^K$) under different treatments in 0–15 cm soil layer was in the following order: 100% NP > 100% N > Control > 100% NPK + FYM > 100% NPK. The $PBC^K$ values in all the treatments showed a rise with depth of soil being maximum in 90–105 cm soil layer whereas $AR_e^K$ declined with increasing soil depth. The differences in $PBC^K$ values within a profile may be due to variation in the quantity of clay present. Acquaye & MacLean (1986) reported that a high $PBC^K$ tended to be associated with high amounts of clay which represents a major source of K released from the exchange sites. Little change was observed in the values of $PBC^K$ of the different treatments. The soil of the present

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investigation being dominant in an illitic clay mineral might have released K continuously during cropping even in K-fertilized plots. This has led to a small change in the $PBC^K$ values. In general, higher $PBC^K$ of a soil implies that the intensity factor (I) at particular time will be lower but the capacity of the soil to maintain constant intensity throughout the time period is greater. Le Roux & Sumner (1968) also observed decrease in $AR_e^K$ but increase in $PBC^K$ due to plant uptake of K. Addition of potassium had little effect upon the $PBC^K$ values. The $PBC^K$ measurement did not, however indicate the potassium fertility of the soils. This finding is in agreement with the results of other researchers (Sparks & Liebhardt 1981; Beegle & Baker 1987; Assimakopoulos *et al*. 1994).

### *Water soluble + exchangeable K (1 M $NH_4OAc$ K)*

Potassium treated plots resulted in higher water soluble + exchangeable K (1 M $NH_4OAc$ K) concentrations than in the control, N and NP plots throughout the profile, the highest being in NPK + FYM plots (Fig. 2). Several workers have reported increase in exchangeable K content in long-term FYM treated plots possibly due to release of K because of the interaction of organic matter with clay, besides the direct K addition in the available K pool of the soil (Mathur 1997). In the present cropping system of maize–wheat–cowpea fodder, though the K inputs did not match net K removals (Table 3), it is not reflected in 1 M $NH_4OAc$ extractable K even after 27 years. The 1 M $NH_4OAc$ K has increased from its initial value of 0·177 $cmol_c$/kg in the year 1971 to 0·207, 0·198, 0·19, 0·29 and 0·32 $cmol_c$/kg in control, N, NP, NPK and NPK + FYM plots, respectively in the year 1998. This was attributed to release of K from mixed and mineral forms. Doll *et al*. (1965) reported that in most soils, $K^+$ is released from the clay and silt fraction. In less weathered soils rich in mica, the silt fraction may contribute substantially to the $K^+$ supply of crops (Mengel & Rahmatullah 1994). The principal $K^+$ bearing mineral in the present soil is illite and contains interlayer $K^+$ in appreciable amounts. The 1 M $NH_4OAc$ K concentration decreased from 0–60 cm soil depth and thereafter increased. The increase in 1 M $NH_4OAc$ K, $AR_e^K$ and $K_L$ in 60–105 cm layer in all the treatments indicate that K was indeed moving down the profile. In light textured soil additional K may be lost through leaching. Hutton & Robertson (1961) studied the residual effect of K fertilization in two sandy Ultisols and observed an accumulation of K in subsoil from leaching.

### *Potassium uptake and grain yield*

Some depletion of potassium occurred in N, NP and control plots due to removal by the crops (Table 3). Even in plots given K fertilizer the total K removal by the crops far exceeded the amount of K applied. Mean K uptake by crops ranged from 65 kg/ha in untreated plots to 209 kg/ha in 100 % NPK + FYM. Continuous application of N, NP and control plots did not lead to potassium deficiency symptoms in maize, wheat or cowpea, which was ascribed to the progressive release of potassium from non-exchangeable reserve in this soil (Krishna Kumari *et al*. 1984). The non-exchangeable K fraction may have been capable of providing this additional K, especially since high crop demand seems to enhance release (McLean & Watson 1985; Mengel 1985). The non-exchangeable form may be in dynamic equilibrium with the exchangeable K (Sparks 1987) thus meeting temporarily high crop demands during the growing season. Contribution of non-exchangeable K to plant K uptake was about 100 % in control, N and NP plots and was reduced to 49 and 32 % in NPK and NPK + FYM plots, respectively (Table 3). The lower per cent contribution of non-exchangeable K to plant uptake in NPK and NPK + FYM could be due to external supply of 2260 and 3952 kg K/ha, respectively. Maize yield was significantly higher in 100 % N plots over control. However P and K had no significant effect. Whereas, the grain yield of wheat showed marked response in K treated plots. Significantly higher yields of maize and wheat were obtained in 100 % NPK + FYM plots over 100 % NPK showing the benefits of organic manure.

## CONCLUSIONS

Long-term cropping, fertilization and manuring influenced the K supplying power of the top soil and subsoil layers, the effects being more pronounced on top soil. The highest and lowest values of equilibrium activity ratio ($AR_e^K$), labile pool of K ($K_L$), non-specific or immediately available K ($\Delta K_0$) and specific or not immediately available K ($K_x$) were observed in 100 % NPK + FYM and 100 % NP plots, respectively at all depths. Despite low $AR_e^K$ and $K_L$ values in control, N and NP plots, maize, wheat and cowpea did not show any deficiency symptoms thereby indicating that sufficient K is being released from a non-exchangeable K source. Contribution of non-exchangeable K was apparently greater in plots with no fertilizer K. That might create nutritional imbalance if potash fertilization is not adopted to keep such soils fertile and productive. The management practices recommended for these intensively cropped soils should include the use of mineral fertilizers in combination with organic manure to sustain a better soil nutrient balance and higher crop productivity.

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