PN-ABJ-849
ISN 74544

Soil Properties Affecting the Availability of Potassium in Highly Weathered Soils

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ABSTRACT

The interpretation of soil tests for K in highly weathered soils may be improved if the K buffering power is considered in addition to extractable K. This study was conducted to determine if cation exchange capacity (CEC) and humic matter (HM) should be included in the development of more meaningful K availability indices. Seventeen soils from the Coastal Plain, Piedmont, and Mountain regions of North Carolina and two soils from the Amazon Basin of Peru were studied. The buffering power tended to correlate positively with CEC, but that of soils high in HM was lower and less affected by CEC than that of the low-HM soils, indicating a lower capacity to replenish K removed from the soil solution upon depletion of K. The K concentration in the equilibrium solution increased linearly with percent K saturation of the CEC, and high HM soils had a higher concentration of K in the equilibrium solution at any given percent K saturation than low HM ones. A larger portion of extractable K was found in solution as HM increased and CEC decreased. It was noted that high HM soils were behaving similarly to low CEC and low HM ones so the soils were grouped into two categories: (i) soils of low K buffering power, which are those with HM ≥ 1.9% and a CEC ≤ 4.6, and (ii) soils of higher buffering power, which are those with HM < 1.9% and CEC ≥ 4.6. The use of this grouping should improve K fertilizer recommendations in highly weathered soils.

Additional Index Words: **extractable K, K availability index, K buffering power.**

EARLY ATTEMPTS to assess the availability of soil K proposed that an ideal ratio between K and other cations should exist in the soil (Bear et al., 1945; Bear and Toth, 1948). This approach, known as the *basic cation saturation ratio* (BCSR), has been shown to be inappropriate because an ideal BCSR does not exist for all soils (McLean et al., 1983). Woodruff (1955a,b) proposed the energy of exchange of Ca by K as an estimate of the rate of delivery of K ions from the exchange complex of the soil to the growing plant. Presently, K extracted by concentrated solutions of other cations is extensively used to assess the availability of soil K. A 1 *M* NH_4OAc solution buffered at pH 7 is commonly used. However, the partitioning of the NH_4OAc-extractable fraction between the soil solution and exchange sites varies among soils because soil colloids differ in their affinity for K ions (McLean and Watson, 1985). As a result, colloids of high K affinity will have lower K concentrations in the equilibrium solution, or lower intensities, at any given level of extractable K. Due to the weakness of bonds between K and organic matter (Salmon, 1964; Evangelou et al., 1986), a soil in which the CEC arises mainly from organic radicals would have a relatively high K content in solution at any given level of extractable K.

The solution is the primary source of K for plant absorption (Barber, 1984). Although some K moves to the plant by mass flow, diffusion through the soil solution represents the main mechanism supplying K to the soil-root interface (Barber, 1985). The driving force for K diffusion to the root surface is the K activity gradient between the bulk soil solution and the root surface (Barber, 1985). The concentration of K in the bulk solution determines the magnitude of this gradient and the rate of diffusion to the root surface (Silberbush and Barber, 1983).

Critical K concentrations in the soil solution have been proposed by several researchers. Grime et al., (1971) found the optimum K concentration in soil solution to range between 20 and 59 mg L^{-1} depending on soil conditions and type of crop grown. Singh and Jones (1975) found that 95% of the maximum yield of lima beans (*Phaseolus lunatus*), tomatoes (*Lycopersicon esculentum*), celery (*Apium graveolens*) and potatoes (*Solanum tuberosum*) was achieved with 7.2, 7.4, 11, and 13 mg L^{-1} in equilibrium solution, respectively.

The ability of the soil to maintain a nearly constant K concentration, or intensity, in the soil solution when this nutrient is either added to or removed from the solution is known as the K buffering power. Several workers have used the quantity/intensity (*Q/I*) concept, which is the relationship between the amount (*Q*) present and the availability or intensity (*I*), to assess the status of soil K (Beckett, 1964a; Beckett 1964b; Le Roux and Sumner, 1968; Koch et al., 1970; Fergus et al., 1972; Evangelou et al., 1986). The slopes and shapes of the *Q/I* isotherms, as first proposed by Beckett (1964a,b), are useful to describe several soil K parameters. These isotherms are constructed by equilibrating a soil sample with a solution of $CaCl_2$ and increasing the amounts of KCl. A net change, ΔK, in soil K content takes place as the soil equilibrates with the solution to attain a characteristic activity ratio for K, AR^K, defined by the ratio $(a^K)/(a^{Ca} + a^{Mg})^{1/2}$. The AR^K at which $\Delta K = 0$ is the equilibrium activity ratio for K, AR_e^K, which is a measure of the degree of K availability of a solution in equilibrium with the soil. The value of ΔK when $AR^K = 0$ is an estimate of size of the exchangeable pool (Beckett, 1964a,b). The slope of the linear portion of the *Q/I* curve represents the potential buffering capacity, PBC^K. Beckett (1971) presents a very thorough review on the *Q/I* relationships. In agricultural soils where exchangeable K ≪ (Ca + Mg), the PBC^K is linearly related to the CEC and the Gapon exchange selectivity coefficient (Evangelou and Karathanasis, 1986).

Kamprath and Welch (1962) found that the CEC of 18 Atlantic Coastal Plain soils was correlated with their organic matter (OM) content. They also showed that 55% of the total CEC measured at pH 7 came from the OM. Evangelou and co-workers (1986) observed that in soils under no-till systems, accumulations of organic matter caused an increase in CEC. However, this increase was not accompanied by a proportional increase in the PBC^K. This behavior was explained as

Dep. of Soil Science, P.O. Box 7619, North Carolina State Univ., Raleigh, NC 27695-7619. Contribution of the North Carolina Agric. Res. Serv., Raleigh, NC 27695-7601. North Carolina Journal Ser. no. 10-884. Received 30 January 1987. *Corresponding author.

Published in Soil Sci. Soc. Am. J. 52:148-152 (1988).

Table 1. Location of the soils used in the study and their taxonomy.

Soil no.	Region	Taxonomic classification
1	Coastal Plain	Loamy, siliceous, thermic Arenic Paleudult
2 and 3	Coastal Plain	Coarse-loamy, siliceous, thermic Aeric Paleaquult
4	Coastal Plain	Clayey, mixed, thermic Aquic Hapludult
5 and 13	Peru	Fine-loamy, siliceous, isohyperthermic Typic Paleudults
6	Coastal Plain	Fine, silty, mixed, thermic Typic Ochraquult
7	Piedmont	Clayey, mixed, thermic Aquic Hapludult
8	Coastal Plain	Fine-loamy siliceous, thermic Aeric Paleaquult
9	Coastal Plain	Fine-silty, mixed, nonacid, thermic Histic Humaquept
10 and 11	Piedmont	Clayey, kaolinitic, thermic Typic Hapludults
12	Coastal Plain	Clayey, mixed, thermic Typic Umbraquult
14	Piedmont	Fine-loamy, mixed, thermic Fluvaquentic Dystrocrept
15 and 17	Mountains	Clayey, mixed, mesic Typic Hapludults
16 and 19	Piedmont	Clayey, mixed, thermic Typic Hapludults
18	Piedmont	Fine, mixed, thermic Ultic Hapludalf

being the result of the low affinity of organic matter for the K ion (Salmon, 1964) which results in a low Gapon exchange selectivity coefficient that counteracts the CEC effect on the PBC^K (Evangelou and Blevins, 1985).

Several authors have related the CEC of the soil with the PBC^K (San Valentin et al., 1973; Singh and Jones, 1976; Beckett and Nafady, 1967; Sparks and Liebhardt, 1981). However, these attempts have only taken heed of one of the factors that affect PBC^K, the CEC. The origin of the negative charges, be it organic or mineral, should also be considered.

This investigation had the following objectives: (i) to determine the K buffering power of several highly weathered soils; (ii) to determine the K in equilibrium solution (intensity) as related to the NH_4OAc-extractable K and percent K saturation of the exchange complex; (iii) to relate the K buffering capacities of these soils to other soil parameters; and (iv) to determine if inclusion of CEC and humic matter should be considered for the development of K availability indexes of highly weathered soils.

MATERIALS AND METHODS

Seventeen soil samples were collected from the three major physiographic regions in North Carolina: Coastal Plain, Piedmont, and Mountains. The Coastal Plain is composed of sandy to clayey unconsolidated marine and fluvial deposits and occupies about 45% of the state's land area. The Mountains occupy about 16% while the Piedmont constitutes the remaining 39% (Daniels et al., 1984) and their soil materials are residuum from bedrock and locally derived colluvium. Two soil samples were collected from a research station at Yurimaguas, Peru. This station is located in a part of the Amazon Basin that is composed of fluvial deposits. The taxonomy of the soils used in this study is presented in Table 1. Relevant chemical properties of the soils are given in Table 2.

Extractable K was determined by extraction with a 1 *M* NH_4OAc solution at pH 7 using a 1:10 soil-to-solution volume ratio. The mixtures were shaken for 5 min at 200 oscillations per min and filtered for further analysis by flame emission spectrophotometry. Extractable cations, buffer acidity to pH 6.6, and humic matter (HM) were determined by the Agronomic Div., North Carolina Dep. of Agriculture, using procedures outlined by Mehlich (1976, 1984a,b). The CEC was calculated by summation of extractable cations

Table 2. Humic matter, CEC, and selected K data of the soils studied.

Soil no.	Humic matter	CEC	NH_4OAc extractable K	Soil solution K	Slope of K buffer isotherm ($\times 10^4$)
	%	cmol L^{-1}			
1	0.4	2.2	0.102	0.076	949
2	1.9	8.1	0.291	0.220	901
3	0.5	3.6	0.158	0.120	889
4	10	7.2	0.213	0.166	874
5	0.3	2.8	0.157	0.093	862
6	0.3	3.8	0.202	0.151	847
7	0.4	3.7	0.338	0.260	844
8	3.4	8.2	0.135	0.104	832
9	7.5	12.9	0.106	0.058	829
10	0.3	5.9	0.164	0.096	827
11	0.4	4.6	0.138	0.082	806
12	4.0	9.8	0.413	0.253	790
13	0.3	4.6	0.200	0.106	789
14	0.3	6.4	0.389	0.224	748
15	0.5	10.1	0.134	0.044	728
16	0.2	4.8	0.168	0.089	706
17	0.5	8.9	0.160	0.052	644
18	0.2	9.5	0.128	0.049	637
19	0.5	7.5	0.121	0.045	603

and acidity. The K saturation of the CEC was computed as the ratio between NH_4OAc-extractable K and CEC.

A sorption isotherm was constructed for each sample using a modification of Beckett's isotherms (Beckett, 1964a,b) used by Singh and Jones (1975). Three cubic centimeter duplicate samples were equilibrated in 50-mL centrifuge tubes with 30 mL of solution ranging from 0 to 30 mg K L^{-1} in 0.01 *M* $CaCl_2$ at room temperature for 24 h. Six points corresponding to added K rates of 0, 50, 100, 150, 200, and 300 $\mu g\ cm^{-3}$ were used to construct each isotherm. After centrifuging 10 min at 850 × *g*, the supernatant was decanted and analyzed by flame emission spectrophotometry to determine the K content of the equilibrium solution. The K on exchange sites was calculated by subtracting K in the equilibrium solution from the NH_4OAc-extractable K. The ratio of K on exchange sites to that in the equilibrium solution was then used to describe a sorption characteristic of the soil.

Sorption isotherms were constructed by making the change in K concentration of the equilibrium solution a function of the amount of K applied. The change in concentration of the equilibrium solution, ΔK, is the concentration after equilibration with a given amount of applied K minus the concentration of K when none was applied.

RESULTS AND DISCUSSION

Sorption isotherms for the nineteen soils are shown in Fig. 1. The change in the K concentration of the equilibrium solution, ΔK, is plotted against the amount of K added (μg K cm^{-3} of soil). The ΔK at the highest rate of K added (300 μg K cm^{-3} of soil) ranged from 18.1 to 28.5 μg K cm^{-3} in solution.

The slopes of the isotherms in Fig. 1 are inversely related to the soil buffering power, i.e., soils that underwent smaller changes in ΔK at a given K addition have higher K buffering powers. This is graphically represented by lesser slopes of their isotherms. The actual slopes are listed in Table 2. The individual observations are not indicated on the isotherms, but the coefficients of simple linear determination (r^2) were > 0.998 in all cases. Given the good fit of the isotherms, two points could be used to determine the K buffering power of soils of this type.

The practical implications of having a wide range in K buffering capacities are apparent. Equal additions of K fertilizers to soils of varying K buffering capac-

ities would result in unequal increases in the K concentration in the equilibrium soil solution. It seems important, therefore, to consider the K buffering power of the soil if the K concentration of the soil solution is to be increased to a given level by fertilizer additions.

The slopes of the isotherms (inverse of the buffering power) are inversely related to the CEC of the soils (Fig. 2). That is to say that as the CEC increases, the K buffering power also increases. This is in agreement with observations by other authors (San Valentin et al., 1973; Evangelou et al., 1986). Although increases in CEC are accompanied by higher K buffering power, the K buffering power of high and low HM soils appears to be affected differently by the CEC (Fig. 2). Soils higher in humic matter present a lower K buffering power at any level of CEC. This behavior can be related to the low bond strength between K ions and organic matter (Salmon, 1964). This observation is also in agreement with Evangelou and Karathanasis' model (1986) which indicates that the CEC of the soil by itself fails to predict the PBC^K. According to their model, increases in the organic matter content could result in small or null increases in the PBC^K depending on the relative increases or decreases in CEC or K_G (Gapon exchange coefficient) values.

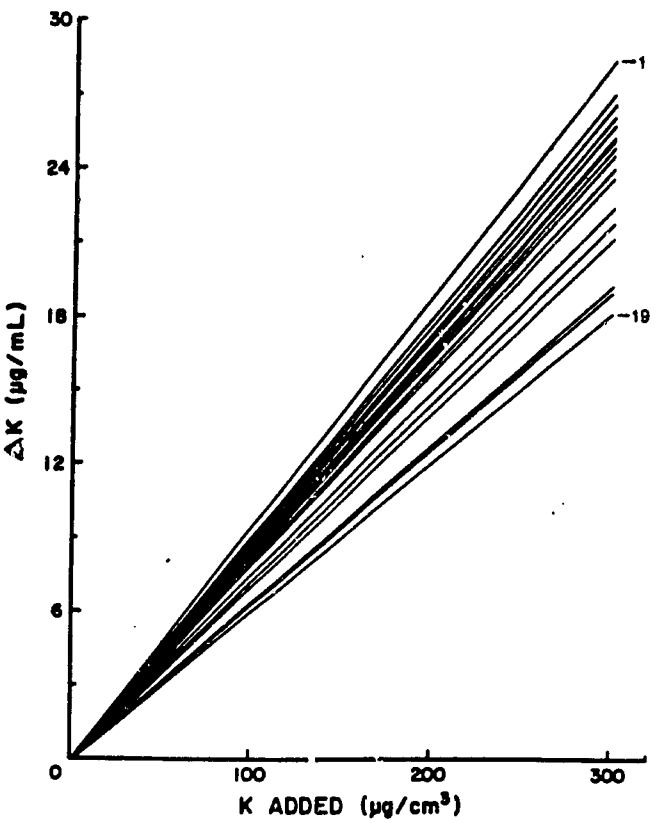

Fig. 1. Change in the K concentration in the equilibrium solution as affected by the rate of K added to the 19 soils. Presented in the same sequence as given in Table 2.

The effect of CEC upon the partitioning of NH_4OAc-extractable K between the exchange sites and the equilibrium solution is illustrated in Fig. 3. With increasing CEC, a higher proportion is found on the exchange sites. The ratio between the K on exchange sites to that in solution is greater for low HM soils, making evident once again the lower affinity of organic colloids for the K ion. This observation has practical implications for the management of K fertilizers in low CEC soils. The partitioning of the applied K in the form of fertilizers between the soil solution and the exchange sites would be controlled by both the CEC of the soil and its humic matter content. When the percent saturation of the CEC was related to the K concentration in the equilibrium solution (Fig. 4), it was observed that for both organic as well as mineral soils the K concentration in the equilibrium solution increased with increasing K saturation of the CEC. However, this increase was more pronounced for organic soils. Greater K contents in the equilibrium soil solution are associated with high HM soils at any percent K saturation. The steeper slope ($P = 0.05$) associated with higher HM content indicates that a greater fraction of the applied K remains in solution when the percent K saturation is increased. Percent K saturation could be used to predict the K concentra-

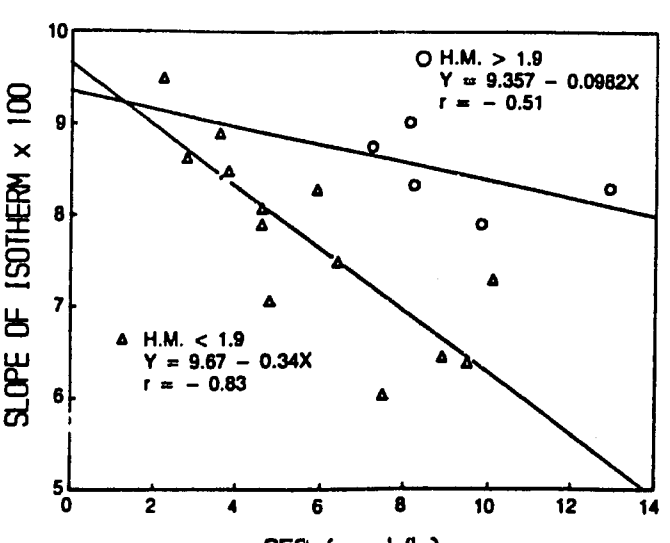

Fig. 2. Effect of CEC on the slope of the K sorption isotherm of the soils grouped by humic matter.

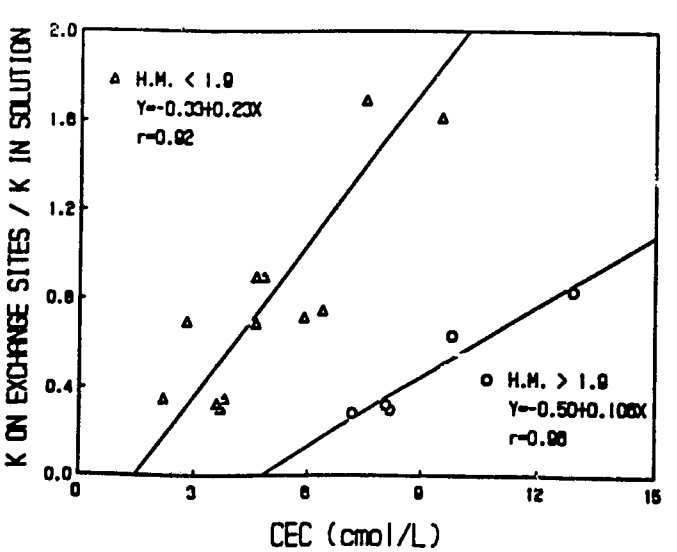

Fig. 3. Effect of CEC on the partitioning of NH_4OAc-extractable K between the equilibrium solution and exchange sites for the soils grouped by humic matter.

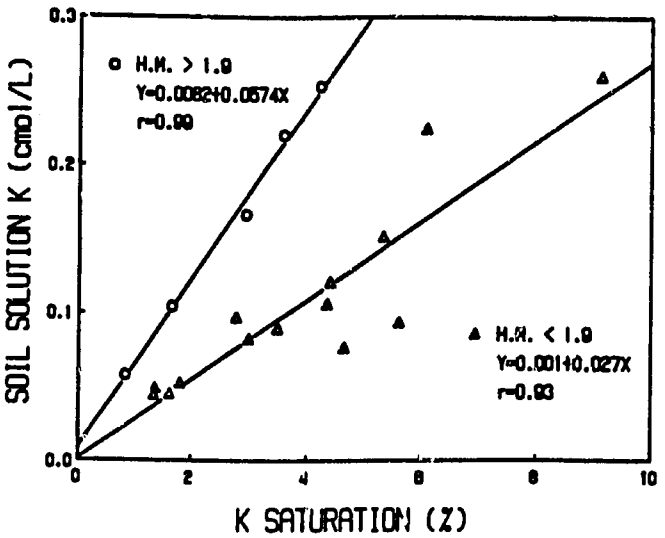

Fig. 4. The relationship between equilibrium solution K concentration and percent K saturation of the CEC for soils grouped by humic matter.

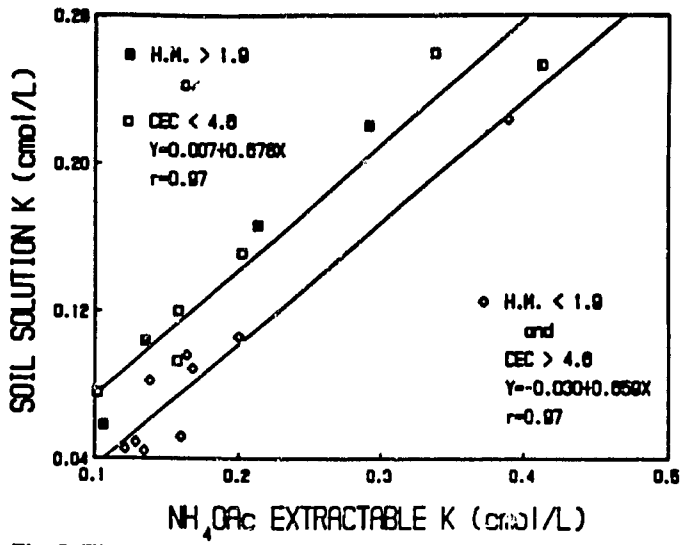

Fig. 5. The relationship between NH_4OAc-extractable K and equilibrium solution K concentration for two groups of soils that differ in their K buffering power.

tion of the soil solution if the HM content is considered.

The effect of CEC and HM content on the K buffering power, and on the fractionation of labile K between the equilibrium solution and exchange sites, indicates that those two parameters could be used as criteria to separate soils into groups for more precise K fertilizer recommendations. It is apparent from the data in Table 2 that soils with isotherm slopes greater than about 0.08, the low K buffering power soils, had either a CEC lower than 4.6 or HM content > 1.9. These criteria can be used to divide the soils into two groups. For each group the relationship between NH_4OAc extractable K and the K concentration in the soil solution was calculated (Fig. 5). Although the slopes are similar, the intercepts differ. There is a higher level of soil solution K associated with the high HM or low CEC soils as compared to the low HM and high CEC soils. As all this information was available from a soil testing laboratory conducting routine analyses, it seems promising that this approach would be useful to refine the K soil test. It further appears that the concept should extrapolate readily to similar highly weathered soils around the world.

It should also be noted that, with minor exceptions, the two groups just described may also be differentiated by physiographic region, hence parent material. The high humic or low CEC soils are from the Coastal Plain (fluvial sediments), whereas the low humic and high CEC soils are from the Piedmont and Mountain regions. This information may be useful to refine soil test interpretations in local situation where humic matter data are not available.

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