Potassium in Atlantic Coastal Plain Soils: I. Soil Characterization and Distribution of Potassium

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ABSTRACT

Corn (*Zea mays* L.) grown on sandy Atlantic Coastal Plain soils is often unresponsive to applications of K fertilizer. As part of a field study on the response of irrigated, intensively managed corn to K applications, we characterized four representative Hapludults from the Delaware Coastal Plain and evaluated their K status. The soils were generally quite sandy with maximum clay contents of 11.4 to 26.5%, had low (≤2.0%) organic matter contents, and had correspondingly low cation exchange capacities (1 to 4 cmol$_c$ kg^{-1} by summation). The clay fractions were dominated by kaolinite and hydroxy-interlayered 2:1 expansible minerals; the latter may play a crucial role in the overall chemistry of K in these soils. The soils were quite high in total K, with means for the four soils (across horizons) ranging from 23.6 to 43.9 cmol$_c$ kg^{-1}, and this was ascribed to the K-rich parent material and relatively young age of these soils. Most (97–98%) of the total K was in mineral forms, and the majority (65–87%) was in the sand fractions, virtually all as K-feldspars. Exchangeable and nonexchangeable (fixed) K levels were relatively low and were of comparable magnitude. Consideration of particle size distribution, K distributions, and published studies of weathering rates suggested that the sand fractions of these soils represent significant sources of plant-available K.

THE ROLE OF K in soils is prodigious. Of the many plant nutrient–soil mineral relationships, those involving K are of major, if not prime, significance. Soil K can be divided into solution, exchangeable, fixed, and structural K (Sparks and Huang, 1985; Sparks, 1987). The proportion of the total K in soils held in solution and exchangeable forms is usually relatively small; the majority of soil K resides in K-bearing micas and feldspars (Sparks and Huang, 1985; Sparks, 1987). The principal K-bearing primary minerals are muscovite, biotite, microcline, and orthoclase; but other micas and feldspars and other minerals may contain substantial amounts of K. In soils, K is also present in nonexchangeable form (preferentially adsorbed) upon reacting and weathered micas, vermiculites, allophane, and zeolites (Sparks and

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Huang, 1985). Potassium can react with Al-hydroxides and acid calcium phosphate solutions to form taranakite (Taylor et al., 1963). In addition, K could be coprecipitated with Al and sulfate to form alunite in acid soils (Adams and Rawajfih, 1977).

A major portion of K in both surface soil and subsoil is transported to the roots from the soil solution through diffusion and mass flow (Barber, 1984). However, the amount of soil solution K is too low to meet the K requirements of a crop over the course of a growing season. Therefore, for optimal K nutrition of a crop, the replenishment of a K-depleted soil solution is affected predominantly by the release of exchangeable K from clay minerals and organic matter. Nevertheless, the stock of exchangeable K is often only large enough to satisfy the requirements of a single crop. Consequently, for maximal crop growth, the soil solution and exchangeable K need to be continually replenished with K through the release of nonexchangeable K, the weathering of K reserves, i.e., micas and feldspars (Sparks and Huang, 1984; Sparks, 1987), or the addition of K fertilizers.

Mengel (1985) has extensively reviewed literature which indicates that, particularly with monocots, nonexchangeable K may represent a significant plant-available pool. Traditionally, it has been thought that only small amounts of K from feldspars and micas were released to plants over a growing season (Rasmussen, 1972; Sparks, 1987). Recently, however, a number of reports have appeared showing a remarkable lack of response to K applications by crops such as corn grown on sandy, Atlantic Coastal Plain soils (Liebhardt et al., 1976; Yuan et al., 1976; Sparks et al., 1980; Woodruff and Parks, 1980). Indeed, Parker et al. (1989, Part II of this study) observed that corn grown on sandy Delaware soils did not respond to K applications over a 3-yr period, despite intensive management and consequent high yields.

The purpose of this investigation was to fully characterize some sandy Delaware soils, and to evaluate the K status of these soils that were used over a 3-yr period for K response studies (Part II of this investigation).

MATERIALS AND METHODS

Studies were conducted on three soils in Sussex County, DE: a Rumford loamy sand (coarse-loamy, siliceous, thermic Typic Hapludult), a Kenansville loamy sand (loamy, siliceous, thermic Arenic Hapludult), and a Sassafras sandy loam (fine-loamy, siliceous, mesic Typic Hapludult); and one soil from Kent County, DE: a Matapeake silt loam (fine-silty, mixed, mesic Typic Hapludult). All four soils are formed in Coastal Plain sediments of fluvial or marginal marine origin and probable late Pleistocene age (Jordan, 1964). Pits approximately 1.5 m deep were dug at each location, the soil profiles described, and bulk samples obtained from each horizon. Samples were stored moist at 277 K until just prior to laboratory analyses whereupon subsamples were air-dried and gently crushed to pass a 2-mm sieve.

Soil Characterization Analyses

After treatment with 30% H_2O_2 to remove organic matter, particle-size distribution was determined by the pipet method (Day, 1965). Organic matter content was determined by wet oxidation with $K_2Cr_2O_7$ (Nelson and Sommers, 1982). Soil pH was measured on a 1:1 soil/water mixture using glass and calomel electrodes. Exchangeable Ca and Mg were extracted with 1 *M* ammonium acetate (NH_4OAc) at pH 7.0, and exchangeable Al with 1 *M* KCl (Thomas, 1982). Exchangeable cations were analyzed by atomic absorption spectrophotometry using standard methods. Cation exchange capacity (CEC) was determined both by summation of the exchangeable K, Ca, Mg, and Al, and by saturation with 1 *M* NH_4OAc (pH 7.0), ethanol washing, NH_4^+ displacement with acidified 10% NaCl, and subsequent analysis by Kjeldahl distillation (Chapman, 1965).

Mineralogical analyses consisting of x-ray diffraction (XRD) and differential scanning calorimetry (DSC) were conducted on the <2-μm clay fraction. Prior to mineralogical analyses, samples were treated with 5.25% NaOCl adjusted to pH 9.5 to remove organic matter (Lavkulich and Wiens, 1970). Iron oxides were removed by Na-citrate-dithionite extraction (Coffin, 1963). Sand was separated from silt plus clay by wet-sieving, and clay from silt by repeated centrifugation and decantation (Day, 1965). Oriented mounts of the clay fraction were prepared by depositing $\approx$250 mg on a ceramic tile as described by Rich (1969). For each sample, one tile was prepared and K-saturated, and another Mg-saturated, both by repeated leaching with 1 *M* KCl and 0.5 *M* $MgCl_2$ solutions, respectively. The Mg-saturated sample was then solvated with glycerol. X-ray diffractograms were obtained using a Diano XRD-800 diffractometer (Woburn, MA) equipped with an LSI-11 computer (Digital Equipment Corp., Maynard, MA). The mounts were scanned at 2° 2θ min^{-1} using Cu $K\alpha$ radiation and a graphite monochromator. The K-saturated tiles were analyzed at room temperature and after heating to 383, 573, and 823 K. The Mg-saturated, glycerol-solvated tiles were analyzed at room temperature and after heating to 383 K. The clay fractions were also analyzed by DSC using a DuPont 1090 Thermal Analyzer (Wilmington, DE). An aliquot of dried clay was heated from 323 to 898 K in an N_2 atmosphere at a rate of 20 K min^{-1}. Kaolinite and gibbsite were quantified by comparison of the DSC peak areas with those of a poorly crystalline Georgia kaolinite and a synthetic gibbsite (Reynolds RH-31F, Reynolds Metals Co., Bauxite, AR). These values were used in conjunction with the peak-area ratios of the XRD patterns to estimate the quantities of the other minerals present.

Distribution of Soil Potassium

Exchangeable K was extracted with 1 *M* NH_4OAc, pH 7.0 (Thomas, 1982). An index of nonexchangeable (plus exchangeable) K was determined by extracting with boiling HNO_3 as described by Knudsen et al. (1982). Total K was determined by grinding whole soil to pass a 0.25-mm sieve, and digestion with HF (Bernas, 1968; Buckley and Cranston, 1971). Additionally, total K in the sand fraction of selected soil horizons was determined. For all fractions, K was determined by atomic absorption spectrophotometry using standard methods. Structural K concentrations were estimated by subtracting the HNO_3 extractable K from total K. The quantity of K-feldspars in the sand fraction of each soil horizon was estimated using a Zeiss petrographic microscope (Carl Zeiss, Inc., Thornwood, NY) with attached 35-mm camera. The sand grains were prepared for optical study by mounting on glass slides in media of known refractive index.

RESULTS AND DISCUSSION

Soil Characterization

Selected chemical, mineralogical, and physical properties of the four soils studied are given in Table 1. The generally sandy textures of the soils were consistent with their fluvial or marginal marine origin (Jordan, 1964). The Matapeake soil contained a silty cap approximately 0.5-m thick of probable aeolian origin and late Pleistocene age (Foss et al., 1978). All four soils had argillic horizons at moderate to shallow depths (Table 1). In the very sandy Rumford and Kenansville soils, clay contents reached a maximum of only 16.1 and 11.4%, respectively, while the Sassafras and Matapeake soils had clay contents as high as 26.5 and 23.6% in their argillic horizons (Table 1). Organic matter contents were low in all surface horizons, ranging from 1.0% in the Rumford soil to a high of 2.0% in the Sassafras soil (Table 1). Cation exchange capacities, due to low clay and organic matter levels, were generally low as is typical of many Atlantic Coastal Plain soils (Yuan et al., 1976; Sparks et al., 1980; Martin and Sparks, 1983).

The mineralogy of the <2-μm clay fraction was generally dominated by kaolinite and chloritized (hydroxy-interlayered) 2:1 clays (Table 1). The latter consisted of chloritized vermiculites, but some horizons (especially subsoil horizons) contained significant quantities of intergrade minerals that expanded with Mg-glycerol treatment. In those case, we have denoted the intergrade component as a chloritized vermiculite-montmorillonite mixture (Table 1). Lesser amounts of quartz, mica, vermiculite, montmorillonite, chlorite, and gibbsite were found in the various horizons (Table 1). "Wedge" sites, which are present in weathered micas, vermiculites, and the chloritized 2:1 clays, are quite specific for K, and for other ions of similar size such as NH_4^+ and H_3O^+ (Rich and Black, 1964). These sites could have greatly affected the K chemistry in the soils we studied. The abundance of chloritized vermiculite in virtually all horizons may thus have played a pivotal role in the dynamics between exchangeable and nonexchangeable K.

Potassium Status of Soils

All four soils contained large quantities of total K throughout their profiles (Table 2). Even in the two sandiest soils, Rumford and Kenansville, total K averaged 23.6 and 43.9 cmol$_c$ kg^{-1} for the two profiles, respectively. Although within the range typical for temperate soils given by Bertsch and Thomas (1985), these levels of total K are considerably higher than those found in Atlantic Coastal Plain soils in Virginia (Sparks et al., 1980) and Florida (Yuan et al., 1976). The sandy surficial sediments of Delaware are most likely derived from relatively K-rich crystalline rocks of the Appalachian mountains and are relatively "young" (and thus not highly weathered) (Jordan, 1964). This may account for the higher total K levels as compared to some similar soils located further south.

The bulk of the total K was in the structural form. Structural K averaged 97, 98, 97, and 98% of the total K for the Rumford, Sassafras, Matapeake, and Kenansville soils, respectively. Based on the petrographic estimates of K-feldspars in the sand fraction, it would seem that the majority of the mineral K was in this form (Table 2); only trace amounts of mica were observed. The quantities of K-feldspar observed were consistent with the findings of Jordan (1964), who reported a mean frequency of 18.4% (range 4 to 39%) in the 0.062- to 0.5-mm size fraction of parent material sediments in Delaware.

Table 1. Selected chemical, mineralogical, and physical properties of the soils studied.

Depth	Horizon	Organic matter	Sand	Silt	Clay	Textural class	pH	Exchangeable			CEC		Mineralogy of <2-μm fraction†
								Ca	Mg	Al	Sum	NH_4OAc	
cm		%						cmol$_c$ kg^{-1}					
								Rumford					
0–25	Ap	1.0	80.6	16.0	3.4	ls	5.3	0.86	0.35	0.14	1.68	2.87	CV = C, K, Q, Mi
25–43	E	0.3	73.1	22.1	4.8	sl	6.0	0.74	0.31	0.09	1.34	2.18	CV, K, C, Q, Mi, G
43–53	BEt	0.3	68.7	22.1	9.2	sl	6.1	1.15	0.45	0.08	1.89	2.80	CV, K, C, Q, Mi, G
53–89	Bt	0.3	62.3	21.6	16.1	sl	6.1	2.77	0.92	0.03	4.05	6.16	CV-Mt, K, Mi, Q, V
89–109	BCt	0.1	66.0	24.9	9.1	sl	6.4	1.38	0.59	0.02	2.20	3.46	K, CV-Mt, Mi, Q, C
109–119	C1	0.1	62.6	29.7	7.7	sl	6.3	1.18	0.51	0.01	1.89	2.79	K, CV-Mt, Mi, Q, C
119–183	2C2	<0.1	90.1	5.2	4.6	s	6.3	0.65	0.18	0.02	0.94	2.79	K, CV-Mt, Mi, Q, C
								Sassafras					
0–20	Ap	2.0	65.5	25.3	9.2	fsl	6.0	2.21	0.77	0.05	3.38	5.17	K, Q, CV, G, MI
20–36	EB	0.5	57.5	27.8	15.0	fsl	5.8	1.57	0.65	0.17	2.76	4.74	K, CV, Mi, Q, G
36–66	Bt	0.2	58.8	14.7	26.5	scl	5.0	1.62	0.65	1.05	3.88	6.66	K, CV, Q = Mi, G
66–84	BC	<0.1	76.3	7.5	16.2	fsl	5.0	1.21	0.46	0.72	2.77	6.89	K, CV-M, Mi, Q, G
84–99	C1	<0.1	76.6	7.6	15.8	fsl	5.2	1.40	0.39	0.41	2.33	5.80	K, CV-M = Q, Mi, G
99–152	C2	<0.1	73.6	13.7	12.7	fsl	5.0	1.22	0.29	0.76	2.37	5.83	K, CV = Mi, Q, G
								Matapeake					
0–25	Ap	1.7	29.6	58.6	11.8	sil	6.1	3.25	1.24	0.02	5.02	7.23	C = K, CV, Mi, Q
25–53	Bt1	0.4	26.2	50.2	23.6	sil	6.3	4.19	1.34	0.01	6.07	9.37	Mt, K, Mi, CV, Q
53–69	2Bt2	<0.1	63.9	20.6	15.5	sl	6.2	2.89	0.66	0.03	3.75	5.45	CV-Mt, K, Q, Mi
69–97	2C1	<0.1	74.0	14.2	11.8	sl	5.3	1.92	0.51	0.42	2.97	4.54	K, CV = V, Q, Mi
97–152	2C2	<0.1	75.7	19.5	4.8	ls	5.3	0.92	0.25	0.16	1.39	2.19	K, CV, Q, Mi, C
								Kenansville					
0–23	Ap	1.3	83.9	14.7	1.4	ls	6.8	2.87	0.49	0.01	3.62	6.09	K, CV, Q, C, Mi
23–58	E	0.2	77.9	19.5	2.6	ls	7.0	1.43	0.41	0.01	2.03	2.78	K, Q, CV = C, Mi, G, Mt
58–71	EB	0.2	84.5	11.2	4.3	ls	7.2	2.08	0.52	0	2.84	4.22	K, CV-Mt, Q, Mi, G
71–86	Bt1	0.1	81.3	7.3	11.4	sl	7.0	2.55	0.49	0	3.30	5.74	K, CV-Mt, Q, Mi, G
86–119	Bt2	<0.1	77.3	12.1	10.6	sl	7.0	3.35	0.43	0	4.03	6.11	K, CV-Mt, Q, Mi, G
119–142	BC	<0.1	82.0	13.5	4.5	ls	7.0	2.43	0.31	0.01	2.99	4.64	K, CV-Mt, Mi, Q
142–162	C	<0.1	89.5	8.2	2.3	s	7.1	1.54	0.21	0	1.96	3.58	K, CV-Mt, Q, Mi

† Order given represents relative abundance, K = kaolinite, V = vermiculite, Mt = montmorillonite, C = chlorite, M = mica, CV = chloritized vermiculite, CV-Mt = chloritized vermiculite-montmorillonite mixture, Q = quartz, G = gibbsite.

The quantities of exchangeable and nonexchangeable K comprised a small percentage of the total K (Table 2). The ratio of NH_4OAc-extractable to HNO_3-extractable K averaged across horizons ranged from 0.32 to 0.56 for the four soils, suggesting that exchangeable and nonexchangeable K levels were comparable. The distribution of K is typical for many Atlantic Coastal Plain soils (Yuan et al., 1976; Sparks et al., 1980; Martin and Sparks, 1983; Sparks, 1987). The rather low amounts of exchangeable plus nonexchangeable K would suggest that some crops might respond to applied K; however, this was not the case for these soils (e.g., Part II of this study).

A large amount of the total K was contained in the sand fraction of selected horizons from these soils (Table 3). Taking into account the percentage of sand in each horizon (Table 1), the data in Table 3 indicate the amount of total K in the sand fractions on a whole soil basis. In the Kenansville loamy sand, for example, 87 and 74% of the total soil K in the Ap and Bt2 horizons, respectively, were contained in the sand fraction. This was also true for the Rumford soil (Table 3, which is also quite sandy (Table 1). In the Sassafras soil, which contained more clay, 65 and 79% of total soil K in the Ap and Cl horizons, respectively, were found in the sand fractions.

The soils studied contained large amounts of structural K that could be supplying K over a period of time to plant roots, and could thus account for the lack of crop response to applied K that is reported in Part II of this study. Two questions can be posed, however. One, what is the rate of K release from these soils, and two, what is the degree of weathering of mineral K? Table 4 is adapted from work of Sadusky et al. (1987), who studied the kinetics and mechanisms of K release from Delaware sandy soils. In this study, K release was modeled from whole soils and different sand fractions using an H-saturated resin. Over a 30-d period, large quantities of K were released from the soils (Table 4). Sadusky et al. (1987) found that K release increased rapidly and then began to level off as an equilibrium was approached.

More K was released from the subsoil horizons than from the Ap horizons of each soil. This can be attributed to a higher clay contents of the former, which are high in vermiculitic minerals (Table 1 and 4). However, significant quantities of K were released from the coarse, medium, and fine sand fractions of the Kenansville soil to the H-resin (Table 4), with the fine fraction releasing the most. If one multiplies the quantity of K released from each sand fraction by its frac-

Table 3. Total K contents of sand fractions and whole soils for selected horizons.

Depth	Horizon	Total K of soil	Total K of sand fraction†
cm		$cmol_c\ kg^{-1}$	
		Rumford	
0–25	Ap	22.5	18.6
89–109	BCt	24.0	16.8
		Sassafras	
0–20	Ap	44.5	29.0
84–99	Cl	46.7	36.7
		Kenansville	
0–23	Ap	35.7	30.9
86–119	Bt2	46.0	33.9

† Expressed on whole-soil basis.

Table 2. Potassium fractions of the four soils studied.

Depth	Horizon	NH_4OAc-exchangeable K	HNO_3-extractable K	Total K	Structural K†	K-feldspars‡
cm			$cmol_c\ kg^{-1}$			Frequency %
			Rumford			
0–25	Ap	0.33	0.49	22.5	22.0	6.7
25–43	E	0.20	0.42	25.0	24.6	9.7
43–53	BEt	0.21	0.47	27.1	26.6	8.0
53–89	Bt	0.33	0.72	25.6	24.9	5.5
89–109	BCt	0.21	0.54	24.0	23.5	8.2
109–119	Cl	0.19	0.51	28.5	28.0	7.3
119–183	2C2	0.09	0.23	12.3	12.1	3.7
			Sassafras			
0–20	Ap	0.35	0.56	44.5	43.9	15.0
20–36	EB	0.37	0.63	39.4	38.8	13.0
36–66	Bt	0.56	0.64	34.7	34.1	15.5
66–84	BC	0.38	0.61	39.8	39.2	14.0
84–99	Cl	0.13	0.36	46.8	46.4	14.8
99–152	C2	0.10	0.35	46.6	46.2	13.9
			Matapeake			
0–25	Ap	0.51	1.07	40.9	39.8	21.0
25–53	Btl	0.53	1.25	42.4	41.2	16.5
53–69	2Bt2	0.17	0.59	39.3	38.7	10.5
69–97	2Cl	0.12	0.53	30.1	29.6	18.5
97–152	2C2	0.06	0.37	27.0	26.6	17.0
			Kenansville			
0–23	Ap	0.25	0.42	35.7	35.3	9.5
23–58	E	0.18	0.40	43.4	43.0	13.0
58–71	EB	0.24	0.48	42.4	41.9	14.5
71–86	Btl	0.26	0.47	44.4	43.9	17.0
86–119	Bt2	0.25	0.49	46.0	45.5	12.0
119–142	BC	0.24	0.41	47.5	47.1	17.0
142–162	C	0.21	0.34	47.9	47.6	16.5

† Structural K = (total K) − (HNO_3-extractable K).

‡ Estimated by petrographic analyses of the whole sand fraction.

Table 4. Potassium released after 30 d from Kenansville soil and sand fractions using H-resin.†

	Whole soil	Coarse sand		Medium sand		Fine sand	
Horizon	K	% of whole soil	K released	% of whole soil	K released	% of whole soil	K released
	mg kg^{-1}		mg kg^{-1}		mg kg^{-1}		mg kg^{-1}
Ap	77.5	43.0	53.6	10.0	65.3	20.5	71.6
Bt2	98.0	24.1	76.2	11.1	69.6	26.7	99.7

† Adapted from Sadusky et al. (1987).

tional percentage of the whole soil in each horizon, and then sums these quantities, some interesting comparisons with the K release by the whole soils can be made. For example, in the Kenansville Ap and B2t horizons, 57 and 54%, respectively, of the total K released can be ascribed to the three sand fractions. If one assumes that the very coarse and very fine sand fractions had K release rates comparable to those of the three fractions given in Table 4, estimates of release by the entire sand fraction are ca. 69 and 65%, respectively, of that by the whole soil. Although these results cannot be readily extrapolated to field conditions, they suggest that if K release occurs in response to high crop demand, the sand fraction could represent a significant source of plant-available K.

In addition, K-bearing minerals appear to be highly weathered in sandy Delaware soils. Sadusky et al. (1987) examined feldspar grains from the sand fractions of several of these soils using scanning electron microscopy (SEM). Deep etch pits were observed on the surface of the feldspar grains, which indicate extensive weathering. These findings, along with the K release data discussed above, suggest that the sand fractions of these soils could be quite important in the overall K balance and K-supplying power of these soils, especially over the course of several growing seasons.

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