Potassium in Atlantic Coastal Plain Soils: II. Crop Responses and Changes in Soil Potassium Under Intensive Management

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ABSTRACT

Corn (*Zea mays* L.) grown on sandy Atlantic Coastal Plain soils is often unresponsive to applications of K fertilizer. The purpose of this investigation was to examine the response of irrigated, intensively managed corn to K applications, and to monitor changes in soil K status. Field studies were conducted for 3 yr at four sites on the Delaware Coastal Plain. Treatments consisted of 0, 94, or 282 kg ha^{-1} applied K, both as a single application and in three split applications. Grain yields were high (6.9 to 14.0 Mg ha^{-1}), but were not significantly ($p \leq 0.05$) affected by K application for any year-site combination. Similarly, corn ear leaves at silking contained adequate K (20 to 30 mg kg^{-1}), although these concentrations varied with K application rate on the two sandier soils. In the zero K plots, dilute double acid-extractable K concentrations ranged from 56 to 194 mg kg^{-1} at the start of the study, and had declined by 29 to 45% by the end of the third growing season. Evidence was obtained for both leaching of applied K and conversion to nonexchangeable forms. The lack of observed yield response was ascribed to (i) modest crop removal of K when corn is harvested only for grain, (ii) adequate K-buffering capacity of these soils to meet high crop demands during the growing season, and/or (iii) availability of significant quantities of subsoil K. Our results further suggested that, despite the high grain yields obtained, current recommendations by several state soil testing laboratories in the region are, if anything, somewhat excessive in that K fertilizer is recommended even when no yield response is observed.

CROPS GROWN ON SANDY Atlantic Coastal Plain soils often show a remarkable lack of response to fertilizer K applications, despite the low cation exchange capacities and exchangeable K concentrations often found in these soils (Liebhardt et al., 1976; Yuan et al., 1976; Sparks et al., 1980; Woodruff and Parks, 1980). This lack of response has been ascribed to several factors, including the availability of subsoil K (Sparks et al., 1980; Woodruff and Parks, 1980), and the release of nonexchangeable and mineral forms of K (Yuan et al., 1976; Parker et al., 1989). The K status of soils is generally quite dynamic, and is influenced by factors such as soil texture, mineralogy, temperature, and pH (Sparks and Huang, 1985). Leaching of applied K can be significant, and seems to be influenced by both soil texture and the quantity of water that percolates through the soil profile (Bertsch and Thomas, 1985).

Irrigated corn production is becoming increasingly common on the mid-Atlantic Coastal Plain, and grain yields of ca. 12.5 Mg ha^{-1} are readily achieved. At these levels of productivity, the aboveground K content of the crop is likely to reach several hundred kilograms per hectare, and the crop demand for this K is often compressed into a brief period of growth (Welch and Flannery, 1985). However, only a fraction of this K is removed from the land in the grain when modern picker-shellers are used for harvest (Welch and Flannery, 1985). At present, it is not known if the general nonresponsiveness of corn to K applications persists when management practices are intensified to achieve these higher yields.

In Part I of this study, we reported the chemical, physical, and mineralogical characteristics of the soils studied, and examined the forms and distribution of soil K. Here, the results of 3 yr of cropping these soils are presented. The specific objectives of this part of the study were (i) to examine the response of irrigated, intensively managed corn to indigenous and applied K, (ii) to study the effect of timing of K applications on crop response, and (iii) to monitor changes in soil K status during and across growing seasons.

MATERIALS AND METHODS

Field studies were conducted from 1982 to 1984 at three locations in Sussex County, DE and at one location in Kent County, DE. Classification and characterization of the four soils have been reported in a companion paper (Parker et al., 1989). Crop response data were obtained for all 3 yr on the Rumford (coarse-loamy, siliceous, thermic Typic Hapludult) and Matapeake (fine-silty, mixed, mesic Typic Hapludult) soils. Due to changes in cooperating growers' plans, plots were cropped in 1982 and 1983 only on the Sassafras (fine-loamy, siliceous, mesic Typic Hapludult) soil, and in 1982 and 1984 only on the Kenansville (loamy, siliceous, thermic Arenic Hapludult) soil. Moreover, yield data could not be obtained in 1984 on the latter soil, although soil and plant analyses were performed.

Crop Response Studies

Field studies were initiated on the four soils in April 1982 and continued through 1984. There were five K treatments: 0, 94, and 282 kg K ha^{-1} as a single preplant application, and 94 and 282 kg K ha^{-1} split into three equal applications, all as KCl. The three splits were applied before planting, when the corn was 0.75 m high, and at the onset of tasseling. Plots 12.2 by 4.6 m consisting of six rows spaced 0.76-m apart were arranged in a randomized block design with four replications. Corn ('Pioneer 3382') was overseeded in mid-to-late April, and after emergence, was thinned to a uniform population between 69 160 and 74 100 plants ha^{-1} at each site. All plots received yearly applications of 49 kg P ha^{-1} as triple superphosphate and 67 kg S ha^{-1} as ammonium sulfate before planting. Nitrogen applications consisted of 59 kg N ha^{-1} as ammonium sulfate and from 55 to 144 kg N ha^{-1} as ammonium nitrate before planting, followed by side-dressing and/or applications in irrigation water using either granular NH_4NO_3 or urea–NH_4NO_3 solution. The exact N-application program varied between sites and from year to year, but the total N applied was 303 to 337 kg ha^{-1} in all cases. All preplant fertilizer was broadcast by hand and disked-in to a depth of 0.15 m. Micronutrients were applied as a foliar spray twice per season—once when the corn was 0.25 m high and once when 0.75 m high. Each application

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Published in Soil Sci. Soc. Am. J. 53:397-401 (1989).

provided 0.56 kg ha^{-1} each of Mn and Zn, both as the sulfate, and 0.56 kg B ha^{-1} as Na-borate. Lime was applied by the cooperating growers as needed to maintain a soil pH of 6.0 to 6.3. Weed control was achieved through the growers' herbicide and cultivation programs. Insects were controlled by one or two applications per year of methyl parathion ('Pencap-M') at a rate of 1.56 kg a.i. ha^{-1}. All plots received irrigation from either center-pivot or traveling-gun systems according to the growers' irrigation schedule for corn.

Grain yields were determined by hand-harvesting 9.2 m of the center two rows of each plot. Seven ears per plot were retained for determination of shelling percentage and moisture content. Reported yields are corrected to 15.5% moisture. The remaining grain in the plots was mechanically harvested, and the stover was left in place until the following spring, when it was plowed down or disked in. Plant samples (10 per plot) were taken at three growth stages: (1) whole plant tops when the corn was 0.2 m high; (2) the first fully expanded leaf below the whorl at the onset of tasseling; and (3) the ear-leaf at early silking. All plant samples were dried at 338 K and ground to pass a 0.86—m sieve. One-half-gram subsamples were digested with a mixture of HNO_3 and $HClO_4$, diluted and analyzed for K by atomic absorption spectrophotometry using standard methods.

Soil Analyses

Soil cores 2.5 cm in diameter were taken from each plot at depths of 0 to 0.2, 0.2 to 0.4, 0.4 to 0.6, and 0.6 to 0.8 m. Samples were collected before planting and periodically through the growing season each year at a frequency of seven cores per plot. In addition, a final sampling was made in November 1984 after grain harvest at a frequency of 15 cores per plot. Data for only the initial (April 1982) and final (November 1984) samplings are reported here. For the initial sampling, the data (Fig. 1-3) reflect the means of all 20 plots at each site prior to application of any K fertilizer. The collected samples were thoroughly mixed and stored at field moisture content at 277 K until just prior to analyses, at which time they were air-dried and gently crushed to pass a 2-mm sieve.

Extractable K was determined by the dilute-double-acid (DDA) or Mehlich I method (Council on Soil Testing and Plant Analysis, 1974) using 5 g soil and 25 mL of a solution 0.0125 M in H_2SO_4 and 0.05 M in HCl. Exchangeable plus nonexchangeable K was extracted with boiling HNO_3 as described by Knudsen et al. (1982). As an additional index of available K, soils were extracted with 1.0 M NH_4Cl. Ten grams soil and 50 mL of solution were shaken for 30 min, filtered, and the filtrate analyzed for K. Potassium analysis was via atomic absorption spectrophotometry using standard methods.

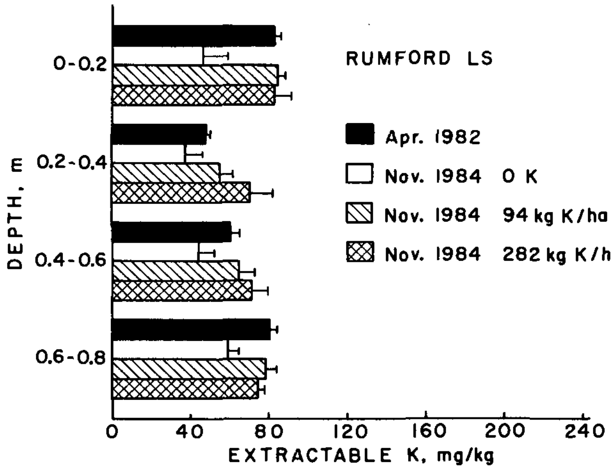

Fig. 1. The DDA-extractable K in the Rumford soil at the initiation and end of the 3-yr study. Error bars indicate standard error of the mean.

Statistical Analyses

Data were analyzed using standard analysis of variance (ANOVA) procedures (SAS Institute, 1985). For grain yields, standard error of the means (SEMs) are presented, and for plant tissue K concentrations, protected least significant differences (LSDs). For the extractable soil K data presented in Fig. 1 to 3, the sampling scheme described above led to an unbalanced data set. Consequently, for each year-site-depth-K rate combination chosen for presentation, only the mean and SEM are presented.

RESULTS AND DISCUSSION

Crop Responses

Due to irrigation and intensive management, corn grain yields were high for all site-year combinations (Table 1). For these soils, especially the sandier ones, yield goals for unirrigated corn are typically only about 4.7 to 6.3 Mg ha^{-1} (Parker and Cotnoir, 1984). No statistically significant ($p \leq 0.05$) increases in yield due to K applications were observed for any year-site

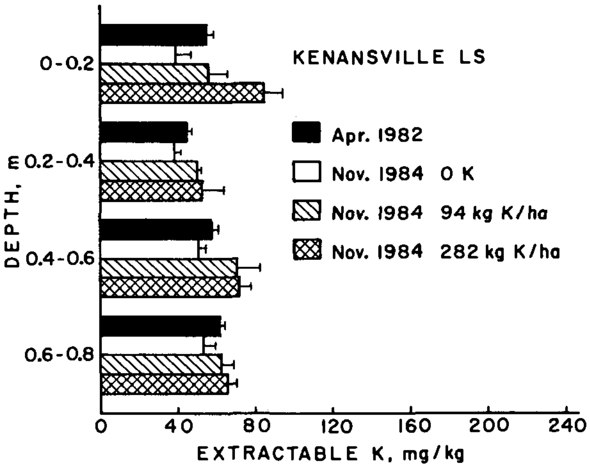

Fig. 2. The DDA-extractable K in the Kenansville soil at the initiation and end of the 3-yr study. Error bars indicate standard error of the mean.

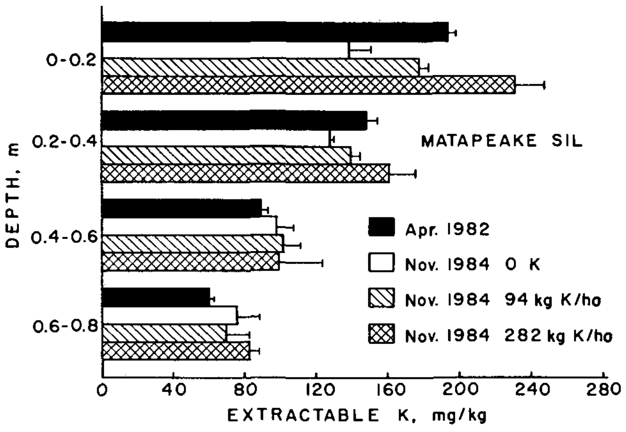

Fig. 3. The DDA-extractable K in the Matapeake soil at the initiation and end of the 3-yr study. Error bars indicate standard error of the mean.

combination (Table 1). On the Rumford soil there was a consistent trend for slightly higher yields with applied K, and in 1983 and 1984 these increases were significant at the $p \leq 0.10$ level. No consistent trends for increased yields were observed for the other three soils (Table 1). The general lack of yield response to applied K is consistent with other reports on corn grown on sandy Atlantic coastal plain soils (Liebhardt et al., 1976; Yuan et al., 1976; Sparks et al., 1980; Woodruff and Parks, 1980).

Of the plant tissue analyses, only those for the ear leaves at silking will be presented; the other samplings yielded similar trends. Applied K increased tissue K concentrations on the two sandiest soils—Rumford and Kenansville—but not on the finer-textured Sassafras and Matapeake soils (Table 2). Virtually all of the ear leaf K concentrations were within the sufficiency range of 20.0 to 27.5 g kg^{-1} reported by Donohue and Hawkins (1979b), consistent with the absence of any yield responses. The observed tissue K concentrations were generally reflective of the K fertilizer treatments. That is, the control treatments consistently resulted in the lowest tissue K concentrations, while the applied K treatments resulted in higher concentrations (Table 2). At either the 94 or 282 kg ha^{-1} K application rate, tissue concentrations tended to be higher when all of the K was applied prior to planting (Table 2). This finding suggests that there would be little or no advantage in using split K applications on similar, but K-responsive, soils.

On the Kenansville soil in 1984 the corn crop was grown to maturity and harvested, but we were unable to obtain the corresponding yield data. However, the tissue K concentrations were all in excess of 20.0 g kg^{-1}, and were quite similar to those observed for other year-site combinations where no response to applied K was observed (Table 2). It thus seems unlikely that any substantial response to applied K would have occurred on this soil in 1984, and we shall also treat it as nonresponsive.

For comparative purposes, we have tabulated the recommended K fertilizer rates from four mid-Atlantic state soil testing programs based on the spring soil samplings (zero K plots only) in 1982 and 1984 (Table 3). All four laboratories use the DDA extraction procedure, although the Delaware and North Carolina recommendations are based on a volumetric measure (see Tucker and Rhodes, 1987). We corrected our gravimetric results to a volumetric basis by experimentally determining the "bulk density" of a scooped sample for each soil. The North Carolina and Virginia recommendations are for unirrigated corn; that is no increase in K rate is recommended due to the higher yield potential with irrigation. The Delaware recommendations are for irrigated corn with a yield goal of 11.0 to 12.5 Mg ha^{-1}. These three laboratories tended to recommend similar small "maintenance" applications of K for several of the soils (Table 3). The Maryland recommendations, which also take into account a yield potential of 11.0 Mg ha^{-1}, are for considerably higher rates of K fertilizer. Our data would suggest that no "upward" changes in soil test calibration are needed for high-yielding irrigated corn grown in this region. That is, current recommendations reflect, if anything, K fertilizer applications that are unnecessary for achieving maximum yields of corn grain. Declines in DDA-K in the plow layer do not seem excessively rapid in these soils (see below), and routine annual soil testing should be able to detect the onset of K-deficient conditions.

Table 1. Effect of K applications on corn grain yields at four sites over three growing seasons. Yield was not significantly ($p \leq 0.05$) affected by treatment for any year-site combination.

Annual K Application†	Soil Rumford	 Kenansville	 Matapeake	 Sassafras
kg K ha^{-1}	yield, Mg ha^{-1}			
		1982		
0	13.1	12.4	12.1	13.1
94	13.4	12.3	11.3	12.9
94S	14.0	12.3	11.7	13.0
282	13.5	11.4	11.1	13.1
282S	13.8	11.4	11.2	12.2
SEM‡	0.3	0.5	0.4	0.4
		1983		
0	8.9	—	12.7	9.2
94	9.4	—	12.5	9.1
94S	8.5	—	12.1	7.6
282	11.5	—	11.8	6.9
282S	11.5	—	12.2	6.9
SEM	0.9	—	0.4	1.2
		1984		
0	9.8	—	8.7	—
94	10.1	—	9.2	—
94S	10.3	—	9.8	—
282	10.0	—	9.4	—
282S	10.5	—	9.3	—
SEM	0.2	—	0.4	—

† S indicates K was applied in three equal portions to give the total rate indicated.

‡ Standard error of the mean.

Table 2. Effect of K applications on K content of corn ear leaves at silking at four sites over three growing seasons.

Annual K application†	Soil Rumford	 Kenansville	 Matapeake	 Sassafras
kg K ha^{-1}	mg K kg^{-1}			
		1982		
0	21.5	22.7	24.6	21.1
94	23.6	25.4	25.8	21.9
94S	21.1	23.0	25.6	22.3
282	23.8	26.7	26.3	23.8
282S	22.8	24.4	26.6	22.4
LSD (0.05)	1.6	1.6	NS	NS
		1983		
0	23.8	—	25.2	22.3
94	28.7	—	25.2	24.9
94S	26.8	—	27.1	22.9
282	30.3	—	26.0	25.4
282S	29.6	—	25.5	23.1
LSD (0.05)	3.4	—	NS	NS
		1984		
0	20.5	21.3	21.9	—
94	23.0	25.2	23.8	—
94S	22.7	23.6	23.5	—
282	24.9	27.5	24.5	—
282S	24.9	25.2	24.2	—
LSD (0.05)	2.5	1.9	NS	—

† S indicates K was applied in three equal portions to give the total rate indicated.

‡ Least significant difference, where NS indicates nonsignificant ($p > 0.05$) *f*-test for effect of K application.

Table 3. Interpretation of plow-layer soil test results and K fertilizer recommendations by four mid-Atlantic state soil testing laboratories.†

		Delaware		Virginia		North Carolina		Maryland	
Soil	DDA-K	Interpretation‡	K rate§	Interpretation	K rate	Interpretation	K rate	Interpretation	K rate
	mg kg^{-1}		kg ha^{-1}		kg ha^{-1}		kg ha^{-1}		kg ha^{-1}
				April 1982					
Rumford	83	H	0	M+	40	H	20	H	110
Kenansville	56	M-H	30	M	55	M	55	H	110
Matapeake	194	VH	0	VH	0	H	0	VH	85
Sassafras	88	H	0	M+	40	H	25	H	110
				April 1984					
Rumford	60	H	45	M	55	M	45	H	110
Kenansville	42	M	65	M−	75	M	75	M	140
Matapeake	155	VH	0	VH	0	H	0	VH	85

† Sources: Delaware, Parker and Cotnoir (1984); Virginia, Donohue and Hawkins (1979a); North Carolina, Tucker and Rhodes (1987); Maryland, Anonymous (1981).

‡ M = medium, H = high, VH = very high.

§ Rounded to nearest 5 kg ha^{-1}.

Changes in Soil Potassium

Due to the enormous quantities of soil K data accumulated during this study, we have selected only the most instructive for presentation here. Specifically, the discussion will primarily focus on the Rumford, Kenansville, and Matapeake soils, and the initial (spring of 1982) and final (autumn of 1984) soil samplings. Only the 0, 94, and 282 kg K ha^{-1} treatments will be considered; the split applications of K did not result in substantially different findings. Moreover, only the DDA-K data will be presented in detail. The boiling HNO_3 and NH_4Cl extraction procedures yielded data that were highly correlated with the DDA-K data, and did not provide much additional information.

The DDA-K concentrations in the zero K plot plow layer (0–0.2 m) samples declined over the study period. By the autumn of 1984, DDA-K had decreased by 45, 32, and 29% in the Rumford, Kenansville, and Matapeake soils, respectively (Fig. 1–3). The DDA-K concentrations in the spring of 1983 and 1984 were intermediate between the initial and final levels depicted in Fig. 1 to 3 (Table 3 and data not shown). For all three subsurface depths in the check plots, the Rumford and Kenansville soils exhibited trends for decreased concentrations of DDA-K (Fig. 1 and 2). In the Matapeake soil, subsoil decreases in DDA-K were apparent only at the 0.2- to 0.4-m depth (Fig. 3), which approximately corresponds to the Bt1 horizon in this soil (Parker et al., 1989). These decreases can be ascribed to crop removal, transformations of K to nonexchangeable forms, or, in the two sandier soils, possible leaching out of the soil profile (Bertsch and Thomas, 1985).

In the Rumford soil, three annual K applications of either 94 or 282 kg ha^{-1} resulted in maintenance of DDA-K concentrations approximately the same as initial levels at three of the four sampling depths (Fig. 1). An increase relative to the initial concentration was noted for the 0.2- to 0.4-m depth (Fig. 1), which corresponds to the E horizon in this soil (Parker et al., 1989). Similarly, two applications of K maintained DDA-K at near-initial concentrations for all four sampling depths in the Kenansville soil (Fig. 2). For the November 1984 samplings, both K rates resulted in higher DDA-K concentrations than in the control plots throughout the profiles of these two soils. This finding suggested that leaching of applied K can be substantial in these sandy soils, consistent with other reports (see Sparks and Huang, 1985; Sparks, 1987). However, the DDA-K concentrations did not tend to reflect the threefold difference in K application rates, suggesting that much of the K applied at the 282 kg ha^{-1} was converted to nonexchangeable forms. The clay fractions of these soils are high in 2:1 intergrade minerals (Parker et al., 1989), which may provide substantial "sinks" for solution and exchangeable K (Sparks, 1987).

In contrast, the finer-textured Matapeake soil exhibited increases in DDA-K due to K application only in the top 0.4 m of the profile (Fig. 3), corresponding to the Ap and Bt1 horizons. The higher clay content of this soil inhibited leaching of K into the lower depths. Again, however, the final DDA-K concentrations did not fully reflect differences in K application rate, indicating conversion to nonexchangeable forms.

The declines in DDA-K throughout the profiles in the zero K plots indicate that, with adequate moisture from irrigation, root proliferation occurs to sufficient depth to draw on K reserves in the subsoil. Applied K appears to be leached to considerable depth in the sandier soils, where it may be retained in exchangeable or nonexchangeable forms. If this K is not ultimately leached to below the rooting zone, it should represent a pool of plant-available K to subsequent crops. Similarly, Woodruff and Parks (1980) suggested that subsoil K should be taken into account when the argillic horizon occurs within 0.5 m of the surface in sandy coastal plain soils.

Having elucidated some of the changes in soil K status that occurred during this study, it may now be instructive to consider the cause for the lack of any observed yield response to applied K. First, we consider the hypothesis that exchangeable K was sufficiently high, and crop removal of K small, over the 3-yr study period. The total declines in DDA-K (summed over the four sampling depths) can be estimated from the zero K plot data in Fig. 1 to 3, and assumed bulk densities of 1.3 g cm^{-3} throughout the profiles. The resulting estimates are losses in DDA-K of 226, 109, and 143 kg K ha^{-1} for the Rumford, Kenansville, and Matapeake soils, respectively. The only K removed by the crop was in the grain, the stover having been left in place. Welch and Flannery (1985) gave a range in K content of 3.0 to 5.1 k kg^{-1} for corn grain, while Sparks et al. (1980) reported contents of about 2 g kg^{-1}. We used a figure of 4 g K kg^{-1} of grain, the yield data in Table 1, and an estimated yield of 10 Mg ha^{-1} for the Kenansville soil in 1984 to estimate crop removal of K. The estimates were 127, 90, and 134 kg K ha^{-1} for the Rumford, Kenansville, and Matapeake soils, respectively, suggesting that the crop removal of K was less than or equal to the decreases in DDA-K. Consequently, there is little to suggest that large, irreversible releases of nonexchangeable or mineral K occurred during the study period to replenish losses due solely to removal in the harvested grain.

However, the foregoing analysis has considered only the final removal of K by the corn grain. During the growing season, the plant demand for K is considerably more, the K in the grain comprising only about 20% of the total in the aboveground portion of the plant at maturity (Welch and Flannery, 1985). Presumably, the K-buffering capacity of these soils was adequate to meet this demand. The nonexchangeable K fraction may have been capable of providing this additional K, especially since high crop demand seems to enhance release (McLean and Watson, 1985; Mengel, 1985). For the samples from the sandier soils depicted in Fig. 1 and 2, the ratio of HNO_3-extractable K to DDA-K averaged 3.49 across all samples. Thus, the DDA-K was only about 22% of that extractable with boiling HNO_3, suggesting that even these sandy soils can accumulate considerable reserves of K in nonexchangeable form. The latter may be in dynamic equilibrium with the exchangeable K (Sparks, 1987), thus meeting temporarily high crop demands during the growing season, but without any attendant increases in DDA-K concentrations in samples taken after the growing season. Moreover, release rates of mineral K from the sand fractions of these soils appear to be substantial (Parker et al., 1989), and may have contributed to the K-buffering capacity during cropping.

SUMMARY

The absence of corn yield responses to applied K on sandy Atlantic Coastal Plain soils reported here and elsewhere may be ascribable to some or all of the following factors:

1. Only modest crop removal of K when corn is harvested for grain only, even at very high yields.
2. Adequate K-buffering capacity due to nonexchangeable and/or mineral forms that meet temporarily high crop demands for K during the growing season.
3. Substantial quantities of subsoil K that seem to be plant-available. Thus, despite the apparent mobility of K in these soils, applied K that is lost from the plow layer may often be held "in reserve" in the subsoil for subsequent crop use.

In addition, our results suggest that no drastic revision of K soil test interpretations is necessary for high-yielding irrigated corn. Current recommendations by several state soil testing laboratories in the region may be somewhat excessive in that K fertilizer is recommended even when no yield response is observed.

ACKNOWLEDGMENTS

This research was supported by a gift from the Potash and Phosphate Institute. We are most grateful to Dale Figgs, Alan Figgs, Mike Daisey, and Kenny Moore for the use of their land and for their excellent cooperation in managing the field plots. We also thank Annemarie Forrest, Charles Toner, John Allen, Sinclair Adam, Ted Carski, and Richard Ogwada for their valuable assistance in both the field and laboratory studies.

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