Cation Exchange Capacity and Starter Potassium Effects on Uptake and Yield

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Introduction and Objectives

Potassium (K) is an exchangeable nutrient considered to be plant available but depends on soil moisture to be carried to plant roots. Soil moisture and nutrient holding will vary with cation exchange capacity (CEC), particularly on sandy soils. Across Delmarva, the CEC can vary from very low (< 2 meq 100g soil^{-1}) to adequate (> 6 meq 100g soil^{-1}), and K plant availability may also vary in these soils.

Another issue with low CEC soils is the availability of Ca and Mg and their competition with both soil exchange and plant uptake. It is well established that K and Mg uptake can be antagonistic, and raising K levels in a low CEC soil may also reduce Mg uptake in the soybean plant. There may be no adequate solution for K and Mg levels in low CEC soils, however we may be able to find the least yield limiting option. The objectives of this study were to plant soybeans in low (<4 CEC) and higher (>4 CEC) zones with and without K application and examine yield and nutrient uptake. This was performed on a low K soil.

Methods

Soybeans were planted (Axis 3922E3) at the Warrington Irrigation Research Farm in Harbeson, DE on June 6, 2023. Soybeans were planted into the subsurface drip irrigated field and placed into zones that were classified as high CEC (>4 meq 100g soil) and low CEC (<4 meq 100g soil^{-1}). These zones were selected based on a previous grid sampling. Within these zones, 10 foot wide plots were established receiving either no K application or 60 lbs K_2O (100 lbs 0-0-60), applied with a Valmar spreader prior to planting (June 2, 2023). Soybeans were planted in 15” rows at a rate of 120,000 seeds per acre. Pre and post-soil samples were obtained from each plot at a 8 inch depth. Vegetative (V3) and reproductive (R2) tissue samples were obtained from the most recent trifoliate leaf. Yields were collected with a plot combine in the late fall. Data were analyzed in SAS as a completely randomized design structured by a factorial of potassium application by CEC zone using Proc GLM. Yield and other factors were also correlated using Proc Corr.

Results and Discussion

Initial Differences in Soil Characteristics by CEC Zones

The higher CEC zones (> 4 meq 100 g soil^{-1}) had higher concentrations of K, Ca, Mg and S (Table 1). They also had greater organic matter, higher pH, and higher concentrations of Al. Interestingly, P was greater in low CEC zones, also having a higher P-saturation (Table 1). The only other soil characteristics greater in low CEC zones was the % H and Mg on the CEC. Spring soil NO_3 and B did not differ between CEC zones. The Fe concentrations, like all other micronutrients, were also similar between CEC zones.

Table 1: Soil characteristics prior to planting and potassium applications. Nutrient values are in parts per million (mg kg soil^{-1}). P-sat is the saturation of P compared to soil Fe and Al content. Differences are by LSD a = 0.1.

CEC Zone **meq 100g soil^{-1}**	**pH**	**%OM**	**NO_3**	**P**	**K**	**Ca**	**Mg**	**Psat**
>4	5.92 a	1.53 a	4.67	88.1 b	59.25 a	256.13 a	53.37 a	26.82 b
<4	5.81 b	1.23 b	4.91	116.3 a	39.94 b	188.31 b	46.94 b	37.25 a
	0.04	*<0.0001*	*ns*	*0.0002*	*<0.0001*	*0.0001*	*0.047*	*<0.0001*
	S	**B**	**Fe**	**Al**	**%H**	**%K**	**%Ca**	**%Mg**
>4	8.38 a	0.23	119.91	746.64 a	16.38 b	6.69 a	55.18 a	19.44 b
<4	7.44 b	0.21	112.97	680.21 b	18.56 a	5.68 b	51.62 b	21.56 a
	0.0499	*ns*	*ns*	*0.001*	*0.0532*	*0.0025*	*<0.0001*	*0.0005*

The greater macronutrients in the higher CEC zones matches expectations, where nutrients are more likely to be retained and not leached from the soil. This also explains the higher pH, due to reduced leaching of base cations. This does not explain the greater P in the low CEC zones, considering that Fe was similar between zones and Al was lower. However, as observed below with yields, lower CEC can result in lower yields, which may reduce P uptake and removal. Despite greater OM in the higher CEC zones, differences in NO3 and B were not observed, which may indicate reduced mineralization at this point in the season. Sulfur could be explained by higher OM, however it could also be held due to greater CEC.

Plot Yields

There were no differences in yield with or without potash applications, and no interaction of CEC with potash application (Figure 1). Yields did vary by CEC, regardless to K application, being 30 bushels higher when CEC was greater than 4 meq 100g soil^{-1}. This could potentially be related to higher moisture holding capacity of these soils or the greater nutrient content. However, adding K had no effect in either soil type, and yields still averaged 70 bushels in the higher CEC soils. It should also be noted that K concentrations were in the low category for this site (Table 1), so a response to K would have been expected. Mineralogy may be providing additional K.

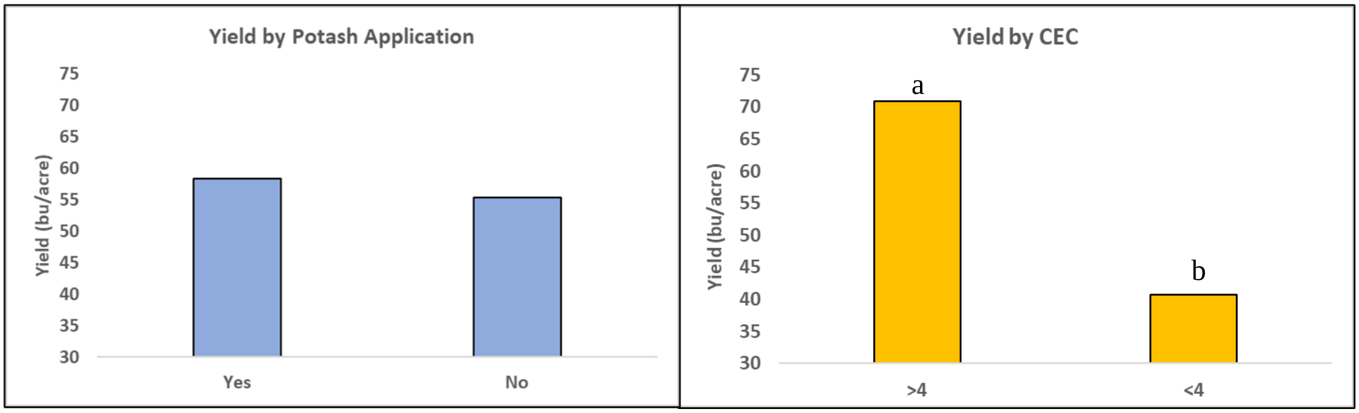

Figure 1: Differences in soybean yield (bu acre^{-1}) by plots receiving potash application (averaged across CEC) and CEC zone (> or< than 4 meq 100g soil^{-1}). For CEC, differences are significant at $p < .0001$.

After Harvest Soil Characteristics by CEC and Potash Treatments

There were no interactions between CEC zone and potash applications, so after harvest characteristics are presently by both CEC and potash applications (Table 2). For potash applications, there were very few differences between soil characteristics (K, %K, and %Ca). Overall, ppm K remained higher with greater CEC, although all values dropped, even with K applications. This makes sense based on yield ranges (30-70 bushels/acre), and estimated uptake of 2.3 lbs K_2O/bu/acre leading to 69-161 lbs K_2O removed from the soil. The differences in Ca on the CEC (%) switched after application, with higher amounts observed on the low CEC soil. Due to the error present in extractions and estimations, this change may not be due to K applications.

Table 2: Soil characteristics prior to planting and potassium applications. Nutrient/element values are in parts per million (mg kg $soil^{-1}$). P-sat is the saturation of P compared to soil Fe and Al content. Percent (%) values represent estimated amount on the CEC. Differences are by LSD a = 0.1.

CEC Zone **meq 100g $soil^{-1}$**	**pH**	**%OM**	**NO_3**	**P**	**K**	**Ca**	**Mg**	**Psat**
> 4	5.9	1.46 a	3.93 a	75.19 b	49.50 a	214.56 a	48.44 a	24.81 b
< 4	5.8	1.05 b	2.04 b	116.69 a	31.81 b	165.88 b	43.13 b	39.31 a
	ns	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*<0.0001*	*0.0742*	*<0.0001*
	S	**B**	**Fe**	**Al**	**%H**	**%K**	**%Ca**	**%Mg**
> 4	6.56 a	0.34	108.40	704.93 a	16.93	6.50 a	54.31 a	20.38 b
< 4	5.69 b	0.35	101.93	642.52 b	19.19	5.06 b	51.06 b	22.38 a
	0.0657	*ns*	*ns*	*0.0067*	*ns*	*0.0062*	*0.0071*	*0.0558*
Potash	**K**	**%K**	**%Ca**	**%Mg**				
60 lbs K_2O	48.94 a	7.06 a	51.63 b	20.75				
None	32.37 b	4.50 b	53.75 a	22.00				
	0.0001	*0.0001*	*0.0678*	*ns*				

For CEC, many of the nutrient levels remained higher with greater CEC (K, Ca, Mg, S) as one would expect (Table 2). A major difference was the greater NO_3 present with higher CEC, with no differences observed in the pre-plant soil samples (Table 1).

Vegetative Stage (V3) Nutrient Concentrations

For early-stage nutrient uptake, there were differences by both CEC zone and potash application, but no interactions between them (Table 3). For CEC, greater concentrations of several nutrients were observed where CEC was higher, including N, K, S, and B. Alternatively, there was no difference in P uptake while Fe and Al were both greater in vegetative stage (V3) leaf tissue with lower CEC (Table 3). This could be related to both nutrient concentrations, but would only explain K, Ca, Mg, and S in the trifoliate leaves. Both the greater N and B could come from soil organic matter with higher CEC, or possibly be related to reduced stress with greater water holding in those soils. This study cannot directly answer that question, but it may also explain why tissue concentrations of Fe and Al were higher in low CEC zones, with stress allowing for greater uptake. Both Fe and Al had lower soil concentrations with lower CEC, so greater uptake indicates another pathway or interaction than simple concentrations. Early season stress may allow for greater Al uptake, which has potentially been observed in planting date studies previously funded by the Delaware Soybean Board.

For potash applications, N, P, Ca, Mg, S, and B all observed reduced concentrations with K applications, while Fe increased. It is possible that early-stage salt concentrations caused stress or reduced uptake. Interestingly, no difference in K uptake was observed at this early stage, which could have explained reduced Ca and Mg in the plant tissue. As such, we can only speculate that, like CEC zones, stress is playing a factor in early season nutrient uptake.

Table 3: Selected **v**egetative (V3 stage) nutrient concentrations in the most recent trifoliate leaf by both CEC zone (> or < than 4 meq 100g soil^{-1}) and potash application. Differences are by LSD a = 0.1.

CEC Zone meq 100g soil^{-1}	%N	%K	%P	S (ppm)	B (ppm)	Fe (ppm)	Al (ppm)
> 4	4.52 a	2.20 a	0.41	0.27 a	25.60 a	466.19 b	985.06 b
< 4	4.22 b	1.99 b	0.40	0.25 b	24.00 b	608.60 a	1307.10 a
	0.0071	*0.0158*	*ns*	*0.0181*	*0.0357*	*0.0077*	*0.0094*

Potash	%N	%P	%Ca	%Mg	S (ppm)	B (ppm)	Fe (ppm)
60 lbs K_2O	4.24 b	0.39 b	0.98 b	0.47 b	0.25 b	23.9 b	591.88 a
None	4.51 a	0.42 a	1.06 a	0.53 a	0.26 a	25.8 a	485.90 b
	0.0148	*0.0582*	*0.0371*	*0.0139*	*0.0425*	*0.0167*	*0.0364*

Reproductive Stage (R2) Nutrient Concentrations

During reproductive stages, trifoliate leaf concentrations taken at R2 had difference relationships with both CEC and potash than the V3 stage. The concentration of N, S, and B were higher within greater CEC zones (>4 meq 100g soil^{-1}), similar to the V3 stage. The tissue concentrations of metals Fe and Al were also still greater in lower CEC zones, but with the addition of Mn during the reproductive stages (Table 4). Most of this could still support that lower CEC zones have additional stress, particularly when considering that there were 30-bushel differences. With that kind of benefit in higher CEC soils, lack of water is the most likely yield limiting factor. One additional factor observed in higher CEC soils was greater Mg uptake in low CEC soils, perhaps indicating that the greater % on the CEC had an effect.

For potash applications, Ca, Mg, S, and B uptake were all reduced when K was applied (Table 4). Although not different at V3, potash applications increased uptake of K by the R2 stage. Copper was also greater with K2O applications, although a reason is not clear. It is not surprising that Ca and Mg uptake was reduced with K application, and this effect has also been observed with B. Whether it had an effect on yield can be observed through correlation analyses (below).

Table 4: Selected reproductive (R2 stage) nutrient concentrations in the most recent trifoliate leaf by both CEC zone (> or < than 4 meq 100g soil^{-1}) and potash application. Differences are by LSD a = 0.1.

CEC Zone meq 100g soil^{-1}	**%N**	**%Mg**	**S (ppm)**	**B (ppm)**	**Mn (ppm)**	**Fe (ppm)**	**Al (ppm)**
> 4	5.4 a	0.50 b	0.26 a	36.3 a	64.0 b	114.8 b	55.3 b
< 4	5.1 b	0.54 a	0.25 b	33.4 b	78.2 a	173.3 a	196.4 a
	0.0076	*0.0067*	*0.0034*	*0.012*	*0.0011*	*0.0016*	*0.0003*
Potash	**%K**	**%Ca**	**%Mg**	**S (ppm)**	**B (ppm)**	**Cu (ppm)**	-
60 lbs K_2O	2.4 a	0.78 b	0.48 b	0.25 b	32.3 b	10.18 a	-
None	1.9 b	0.85 a	0.56 a	0.26 a	37.3 a	9.4 b	-
	0.0001	0.0261	0.0001	0.0233	0.0001	0.0103	-

Factors Correlating with Yield

Correlation indicates the direction and strength of a relationship, so that anything positive means yield is increasing in relation to that variable (Table 5). For yield in this study, similar soil factors were observed for both pre-plant and post-harvest, with K and Ca concentrations being important at both time points for increased yield. Other factors that may be related to soil CEC effects are organic matter content and Al, which were both associated with higher yield for soil concentrations, *but not tissue concentrations.* Therefore, we believe that higher Al associated with CEC zones was the relationship with greater yields. Although NO3 was not different at pre-soil levels, it was higher in those CEC zones as well, and soil concentrations strongly influenced yield (> r = 0.8). It should be examined whether higher NO3 in the soil was due to organic matter or greater holding capacity.

Table 5: Correlations between yield and both soil and tissue characteristics in this study. Considered significant at p = 0.1.

	Positive Correlations
Pre-Soil	pH, OM, K, Ca, %K, %Ca, Al
Post-Soil	OM, NO_3, K, Ca, %K, %Ca, Al
V3	N, K, S, B
R2	N, S, B
	Negative Correlations
Pre-Soil	Psat, P, %H, %Mg
Post-Soil	Psat, P, %Mg
V3	Mg, Mn, Al
R2	Mg, Mn, Fe, Na, Al

For leaf tissue, greater N, S, and B were important at both V3 and R2, while K was only important at V3. This is interesting, as K concentrations were not found to be different at the V3 stage. The three nutrients, N, S and B, are all anions typically associated with higher organic matter. Perhaps supplemental fertility for those nutrients in lower CEC soils is warranted.

Alternatively, negative correlations indicate that yield fell with either higher soil or nutrient cocentrations (Table 5). For soils, both P-sat and P concentrations were associated with lower yield, probably also related to the CEC effect, where lower CEC reduced yields, but also had greater P concentrations. We do not believe that P was affecting yield in this study. As opposed to positive correlations (K and Ca), the Mg in the soil was associated with reduced yields. Although the concentration was low in these soils, the % on the CEC is a bit higher than recommended (~ 20% in this study). This can also be observed in the tissue cocentrations, with Mg being associated with lower yield at V3 and R2. Perhaps either supplemental gypsum or additional K would have reduced the effects of Mg on soybean yield.

Besides Mg, the metals Al, Fe, and Mn were also associated with lower yield when found in the soybean leaf tissue. As noted above, their uptake may be associated with stress in the lower CEC zones, and not have caused yield loss. This cannot be determined in this study.

Conclusions

Even with low K concentrations, yields still averaged 70 bushels with or without K applications, but only when CEC was greater than 4 meq 100g soil^{-1}. The 30-bushel loss associated with lower CEC zones could be lower nutrient concentrations (K, Ca, or Mg), but the differences in nutrients were not that great. Instead, water stress may be the culprit. These soils received subsurface drip irrigation, which may have difficulty wicking up through sandy soils, providing limited benefit. Overhead irrigation may produce different results. The lack of response from K may be associated with the mineralogy of Delaware soils, which have additional K not measured by traditional soil testing.

Water stress appears to have increased the uptake of metals, Fe, Mn, and Al into the leaf tissue, although the mechanism cannot be determined from this study alone. Even with lower CEC's, the addition of K helped yield, probably by reducing Mg uptake. The Mg on these soils was higher than recommended for the CEC (>20%), although there are no set recommendations for % nutrients on the CEC. However, uptake of any nutrient is limited when competing with space on the CEC, which appears to have affected both Ca and K in this case. Studies in additions of Ca or higher K rates could help determine if that is the problem here.

The leachable anions N, S, and B were associated with greater yield when taken into the plant. All three are associated with greater organic matter, which was higher in the greater CEC zones. However, at the end of the season, NO3 was almost twice as high in the >4 CEC, which may be due to nutrient holding as well. Examining the addition of supplemental N, or greater assistance to rhizobia, could be beneficial on low CEC soils.

When returned to soybeans in the rotation, the University of Delaware will pursue future ideas on this site, involving gypsum, ammonium sulfate, or carbon (humic acid) additions.