Exchangeable Cation Uptake by Irrigated and Rainfed Soybeans

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Introduction and Objectives

Although Ca, Mg, and K are all exchangeable nutrients that are considered plant available, soil chemistry and plant root interactions result in different uptake and bioavailability. In particular, K and Mg have antagonistic relationships in both corn and soybeans, with over application of either nutrient suppressing uptake of the other. Within the soil, Ca and Mg can move with soil water or by diffusion, while the lower K concentrations do not readily move with soil water. This results in differences in uptake for soils with adequate moisture versus those under drought stress. Understanding how concentrations of each nutrient, the soil CEC, and soil moisture content interact is important for giving future nutrient recommendations.

The objectives of this study were to sample center pivots in their dry corners and irrigated regions and compare soil nutrient levels and nutrient uptake in the leaf tissue for potential

Methods

Ten different soybean fields with center pivot irrigation were sampled in Sussex and Kent County Delaware in 2021 and again in 2022. In each field, two locations which received irrigation and two locations without irrigation were sampled for both soil nutrient and soybean tissue at approximately R2-R3 growth stages (August 2021 & July 2022). A total of 80 soil and 80 tissue samples were taken for analyses. All fields were full season soybeans.

Samples were dried and sent to the University of Delaware for analyses. Soils were analyzed for the total nutrient suite (macro and micronutrients, NO_3 only in 2022), as well as pH and organic matter content. Plant tissues were analyzed for all macronutrients, selected micronutrients, Al and Na. Total nutrient uptake of Ca, Mg, and K will be compared among rainfed and irrigated samples to observe differences in soil nutrient vs soil moisture effects on uptake.

Cumulative rainfall was obtained from the Delaware Environmental Observing System (DEOS) for Georgetown, DE (Sussex County), Dover SFS (Kent County), the Newark Ag Farm (New Castle County) to represent county averages. They will not capture locally variable rainfall, but are representative of statewide trends. Rainfall in the region varied throughout the state, with lower accumulation over the summer in northern Delaware (Figure 1). Rainfall where most of

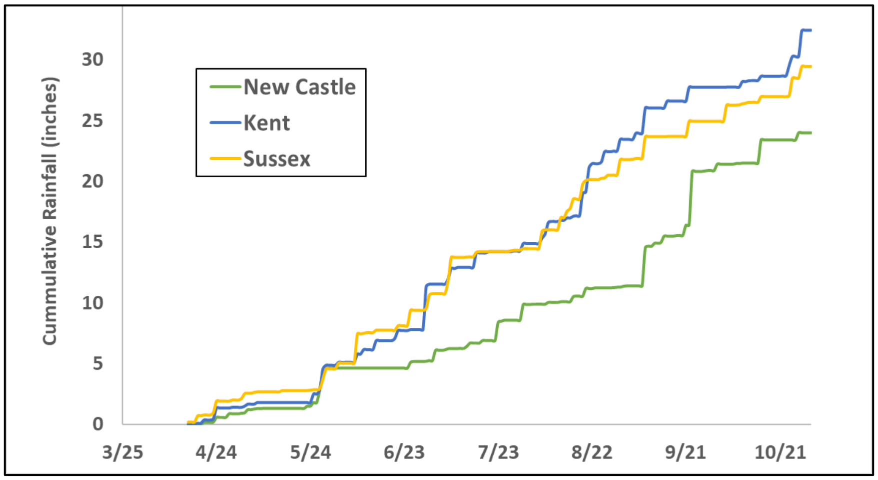

Figure 1: Cumulative rainfall in northern (New Castle), central (Kent), and southern (Sussex) DE over the 2021 growing season.

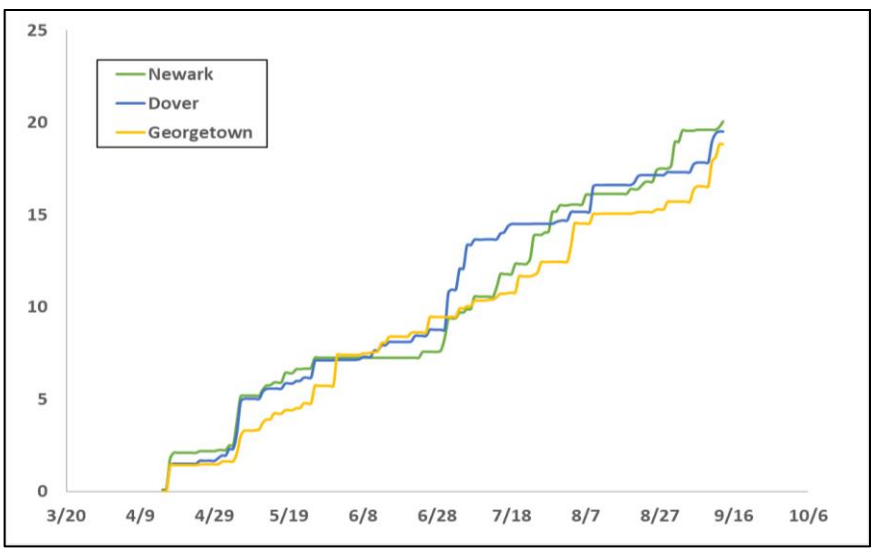

Figure 2: Cumulative rainfall in northern (New Castle), central (Kent), and southern (Sussex) DE over the 2022 growing season.

the fields were sampled (Sussex and Kent) was similar throughout the season, and only really lacking at planting (April and May). A drought period occurred mid-July through early August, just prior to leaf tissue sampling. Hurricanes and larger storm events typically happen August through the fall, and cumulative rainfall continues after the short dry period in late July. Due to this, rainfed conditions may be similar to irrigated fields, as many farms did not turn on irrigation frequently in June and early July (personal communication, local soybean producers.

Rainfall in 2022 was much drier across the state, but particularly in the southern portion. Overall, conditions remained drier, with a stronger drought period occurring in August in Kent and Sussex counties.

Results and Discussion

Soil Characteristics and Nutrient Concentrations

Among the twenty fields sampled, there was no difference in CEC or soil pH between rainfed and irrigated portions of the fields (Table 1). For a study observing uptake of nutrient based on soil moisture, we do not want differences in CEC or soil pH and would not expect irrigation to alter CEC in any meaningful way. It is possible for pH to shift overtime in these fields where irrigation is present, either due to leaching, increasing yields and nutrient uptake, or some other mechanism, but that is not the case in this observational study.

Table 1: Soil Characteristics in Irrigated and Rainfed Portions of Each Field (α=0.1).

	CEC meq/100g	**Soil pH**	**Soil NO_3 (ppm)**	**Soil P (ppm)**	**Soil K (ppm)**	**Soil Ca (ppm)**	**Soil Mg (ppm)**	**Soil S (ppm)**
Irrigated	6.33	5.81	9.2b	220.7	123.17b	702.9	107.8	15.1
Rainfed	6.35	5.77	19.6a	220.7	150.0a	701.2	102.9	16.2
p-value	0.9652	0.6758	*0.0652*	0.1772	*0.0412*	0.9826	0.5749	0.2688
	Soil Mn (ppm)	**Soil Zn (ppm)**	**Soil Cu (ppm)**	**Soil Fe (ppm)**	**Soil B (ppm)**		**Soil Na (ppm)**	**Soil Al (ppm)**
Irrigated	25.6	9.3	6.3	177.2	0.55	-	14.8a	889.1
Rainfed	20.5	9.9	5.9	180.3	0.56	-	12.0b	899.0
p-value	0.3332	0.6807	0.7018	0.8350	0.9500	-	*0.0620*	0.8621

Of the plant nutrients measured in the soil, only NO_3, K, and Na had any significant differences (Table 1). The higher NO_3 measured in the rainfed fields may indicate poor uptake during a drought, but samples were all taken at the R2 growth stage, so prior values cannot be confirmed. Other anions that may come from organic matter include sulfur (as SO_4) and boron (B), but neither differed across rainfed and irrigated parts of Delaware fields.

While the hypothesis of this study was that additional K would be needed in dry corners to assist with uptake, higher values are already present. This may be due to reduced uptake across the corn-soybean rotation with lower yields. If these fields all receive the same rate of potash, reduced K uptake over time could cause a concentration increase in the dry corners. We may expect the same from Ca and Mg, but with higher concentrations in the soil and easier transport could explain why they are not different across rainfed and irrigated portions of the fields

Irrigation water may be the source of additional Na in soils under the center pivot (Table 1). In previously sampled center pivot fields, higher yields were tied to leaf tissue Na concentrations which was attributed to salts in the irrigation water (Miller and Shober, 2020).

Soybean Leaf Tissue Nutrient Concentrations by Irrigated vs Rainfed Conditions

Macronutrient concentrations in the upper leaves of irrigated field regions had higher N and P concentrations compared to rainfed portions of the field, while no other macronutrients were significantly different (Table 2). Of the other macronutrients, only calcium (Ca) was close to any significance and was slightly higher in rainfed portions of the fields. The higher N is probably due to plant and microbial vigor under reduced water stress, which may have also influenced P uptake. Phosphorus availability is limited by its sorption to soil surfaces, so greater moisture provided by irrigation may allow for transport to the root, as well as root interception closer to colloid surfaces.

Table 2: Soybean leaf tissue *macronutrient* concentrations (%) at the R2/R3 growth stage (Fishers LSD, α=0.1).

	N	P	K	Ca	Mg	S
	----------	----------	---------- %	----------	----------	----------
Irrigated	5.64a	0.46a	2.22	0.84	0.34	0.29
Rainfed	5.25b	0.41b	2.16	0.94	0.36	0.28
p-value	*0.0027*	*0.0388*	*0.4229*	*0.1308*	*0.3965*	*0.3740*
*Sufficiency Ranges**	*3.25-5.0*	0.3-0.6	1.5-2.25	0.8-1.4	0.25-0.70	0.25-0.6

In a study observing the differences between rainfed and irrigated fields, K uptake fluctuated in rainfed fields with water availability (Karlen et al., 1982), but was not observed in this study.

Based on weather data over the last two years (Figure 1 , Figure 2), there is reason to believe that drought conditions and variable rainfall could have caused the same issues. Fernandez et al. (2008) also noted that greater water recharge and K availability in the upper 5 cm of the soil with intermittent rainfall provided the greatest K uptake. The explanation may lie in the higher K concentrations in the rainfed portions of the field, which may have helped with uptake under both drier and moister conditions (Table 1).

Although limited uptake of N, P, K and Ca have been reported in the seeds of water stressed soybeans (Wijewardana at al., 2019), there were no differences in Ca within these fields. In these fields, the lack of differences in Ca, Mg, and S between irrigated and rainfed fields is positive, meaning management across the field can be the same, a very dry year may change these results. As S and N are often dissolved in irrigation water and can have correlated uptake within the plant, it is not apparent what mechanism kept S similar between rainfed and irrigated soybeans.

Soybean leaf tissue micronutrient concentrations did not see differences for Mn, Zn, Cu, Fe, B and Mo (Table 3). All of these nutrients were within the center of their sufficiency ranges for both irrigated and rainfed regions of the fields. Although micronutrients sorb to soil surfaces and are relatively unavailable, the addition of moisture through irrigation does not appear to increase uptake.

Table 3: Soybean leaf tissue *micronutrient* concentrations (ppm) at the R2/R3 growth stage (Fishers LSD, α=0.1).

	Mn	**Zn**	**Cu**	**Fe**	**B**	**Mo**
	--------------------------------------- ppm ---					
Irrigated	56.3	66.2	9.7	110.8	44.4	2.7
Rainfed	65.3	73.3	10.8	101.0	46.1	2.3
p-value	*0.3163*	*0.3802*	*0.2414*	*0.2376*	*0.7678*	*0.5253*
*Sufficiency Ranges**	*17-100*	*21-80*	*4-30*	*25-300*	*20-60*	*1-5*

While not an essential nutrients Na was higher in irrigated leaf tissue (Table 4), which may be related to Na salts in irrigation water. As noted above, Na was also greater in the soil under the center pivot. Al is considered a toxic, antagonistic element, and was marginally higher in rainfed leaf tissue (Table 4).

The greater concentrations of Al in the rainfed soybeans (approximately doubled) may indicate that stress during drought allows for more Al uptake (Table 4), particularly where there is decreased access to other nutrients. However, as a metal Fe is also plentiful in soils, and greater concentrations were not observed, along with the metals Cu, Zn, and Mn in either portion of the field (Table 3). It is not clear what caused increased Al uptake in rainfed fields. Free aluminum can cause issues with plant growth due to reactions with roots, so additional Al in leaves could be a concern for yield in rainfed portions of the field. In this case, pH could be raised in dry corners, however, that may also cause limitations in the uptake of Cu and other micronutrient metals.

Table 4: Soybean leaf tissue *Na and Al* concentrations (%) at the R2/R3 growth stage (Fishers LSD, α=0.1).

	Na	**Al**
	------------- ppm ---------------	
Irrigated	13.6a	28.9
Rainfed	5.3b	42.4
p-value	*0.0647*	*0.1108*
*Sufficiency Ranges**	*Not applicable*	*Not applicable*

Correlations for Rainfed and Irrigated Leaf Tissue Nutrients with Soil Nutrient Concentrations

Correlations of soil pH and CEC to leaf tissue nutrients are in Table 5 split by rainfed and irrigated regions of the fields. For both portions of the fields, tissue Mg has a positive relationship with soil pH, while P and K are only affected in rainfed parts of the fields (Table 5).

Soil pH was below 6 averaged across both rainfed and irrigated fields (Table 1), so it's not surprising that minimal relationships with micronutrients exist. In this study, tissue Mn had a negative relationship with soil pH in rainfed and irrigated fields. Even at acidic pH values, our soil Mn levels may be low enough to warrant additions of Mn to maintain crop growth, although values were within sufficiency ranges.

Soil CEC had a negative relationship with tissue Mg concentrations in rainfed fields, while Ca had a positive relationship in irrigated portions (Table 5). Although Mg concentrations were sufficient averaged across tissue samples (Table 2), fields may still be under-fertilized relative to Ca, so that CEC becomes a proxy for this issue. When a nutrient on the CEC is in lower concentration, reduced release or availability from the CEC may occur. This appears to be exacerbated under moisture stress, which may also explain why Ca is more competitive with higher CEC under irrigated conditions.

Table 5: Correlations of soil pH, CEC, and nutrients concentrations (positive and negative relationships) versus all soil tissue nutrients measured (α=0.1). Correlations above 0.5 are in bold while correlations between the same nutrient are in italics.

	Rainfed Soil Nutrients		**Irrigated Soil Nutrients**	
	(+)	**(-)**	**(+)**	**(-)**
Soil pH	P, K, Mg	Mn	Ca, Mg	Mn
Soil CEC	-	Mg	Ca	-
Tissue N	Ca, Mn, B, S, **Na**	-	Zn, Cu	-
Tissue P	K, Ca, Cu, B, S, **Na**, Al	-	*P,* Cu, Fe, Na	-
Tissue K	*K*, Ca, Cu, B, S, **Na**, Al	-	*K*, Fe, B	-
Tissue Ca	B	-	K, *Ca*, Mg, Cu, Fe, **B**, Na	-
Tissue Mg	Cu, Fe, B, Na	-	Cu, Fe, **B**, Na	-
Tissue S	K, Cu, **B**, *S*, **Na**, Al	-	P, Cu, Fe, **B**, *S*, Na, Al	-
Tissue Zn	Zn, Cu	-	P, *Zn*, **Cu**, Fe	Mg
Tissue Mn	-	Ca, Na	Cu	Ca, Mg
Tissue B	-	Na	-	Na
Tissue Na	Zn	K, Cu, **B**, **Na**	Na	K, B
Tissue Al	P, Cu	-	Cu, B	-

Tissue N concentrations had no negative relationships with soil nutrients, but were positively associated with Ca, Mn, B, S, and Na in rainfed corners and Zn and Cu in irrigated centers (Table 5). Since soybeans produce their own N through symbiosis, these nutrients may influence microbial health as well. The higher soil Na associated with greater tissue N concentrations is confusing, but this was also observed for soybean leaf concentrations of P, K, Mg, and S (Table 5). In most cases those correlations were much stronger than others observed (>0.5). For all other tissue macronutrients (P, K, Ca, Mg, and S) there were no negative relationships to soil nutrient concentrations in either center or dry corner parts of the field. Only K and S had tissue concentrations tied to their soil levels in both parts of the fields. Although neither varied in total tissue concentration, it does appear that proper fertility is important and is varying within the fields. Phosphorus, Ca, and Zn were tied to their soil concentrations under irrigated conditions.

Another interesting relationship is that of soil B to nutrient uptake, where tissue P, K, Ca, Mg, and S in rainfed parts of the field were all tied to higher B concentrations. A similar effect was observed in irrigated fields, but soil B was related to tissue K, Ca, Mg, S, and Al, with many relationships above r=0.5. Whether this is due to soil B concentrations or is a corollary to what makes those concentrations higher, cannot be determined from this observational study.

Soil B only had a negative relationship with tissue Na concentrations, possibly indicating it can reduce uptake or replace Na in the uptake pathway. Interestingly, tissue B was also lower when Na concentrations were observed to be higher in the soil (Table 5). Soil Na concentrations also suppressed Na uptake in rainfed fields, but were tied to higher concentrations in irrigated fields, again possibly due to additions of salts from irrigation water. Soil K predicted lower tissue Na in both rainfed and irrigated parts of the field.

Correlations for Rainfed and Irrigated Leaf Tissue Nutrients with Each Other

Under rainfed parts of the field, tissue Na concentrations were tied to lower soybean leaf concentrations N, P, K, Ca, Mg, and S (Table 6). This only occurred for K in irrigated parts of the fields. For the other macronutrients, this may indicate that stress allows for more Na uptake in rainfed parts of the field because it is more likely to be in the soil solution, or that stress just reduced uptake of those nutrient overall. Once irrigation is introduced, it indicates that Na is only competing with K uptake in the soybean plant.

Although soil B concentrations were tied to many tissue macronutrients, tissue B concentrations had negative relationships with N, P and K in rainfed soils and P, K and Mg in irrigated sections (Table 6). This may support the idea that soil B concentrations indicate some other function in the soil assisting with uptake, since the actual uptake of B into the tissue is not related to macronutrient uptake. However, soybean tissue levels of B do have positive relationships with tissue Zn, Mn, Mo, and Na in dry corners. This was only seen for Mo in irrigated soils, and the correlation coefficient was >0.5.

Table 6: Correlations of tissue nutrient concentrations to each other in the soybean leaves (α=0.1). Correlations above 0.5 are in bold.

	Rainfed Tissue Nutrients		**Irrigated Tissue Nutrients**	
	(+)	**(-)**	**(+)**	**(-)**
Tissue N	**P**, **K**, **S**, Mo	B, Na	**P**, S, Zn	-
Tissue P	**N**, **K**, Mg, **S**, Cu, Mo	Mn, B, **Na**	**N**, **K**, **Mg**, **S**, Zn, **Cu**	**B**
Tissue K	**N**, **P**, Mg, **S**, Cu, Fe, Mo	B, **Na**	**P**, **Mg**, **S,** Zn, **Cu**	**B**, Na
Tissue Ca	**Mg**, Zn, **Cu**, **Fe**, **Al**	Na	Mg, S, Zn, Cu, B, Al	-
Tissue Mg	P, K, **Ca**, S, Zn, Cu, Fe, Al	Na	**P**, **K**, Ca, **S**, Zn, **Cu**	B
Tissue S	**N**, **P**, **K**, Mg, Zn, Cu, Fe	**Na**	N, **P**, **K**, Ca, **Mg**, Zn, **Cu**, Fe	-
Tissue Zn	Ca, Mg, S, **Mn**, **Fe**, B, **Al**	-	N, P, K, Ca, Mg, **S**, **Mn**, Cu, Al	-
Tissue Mn	**Zn**, **B**, Na	P	**Zn**, Al	-
Tissue B	**Mn**, Zn, Na, Mo	N, P, K	Ca, **Mo**	**P**, **K**, Mg, Cu
Tissue Mo	N, P, K, B		**B**, Na	**Mg**
Tissue Na	Mn, B	N, **P**, **K**, Ca, Mg, **S**	Mo	K, S, Cu, Fe
Tissue Al	**Ca**, Mg, Zn, **Cu**, **Fe**		Ca, Mn, Zn, Cu	

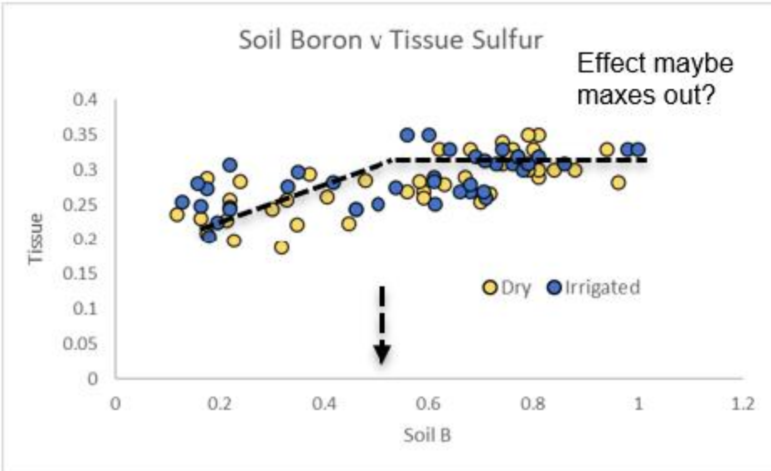

Figure 3: Relationship of soil B to Tissue S under irrigated and dry conditions.

The concentration of soil B at R2 (late July/early August) had a pattern observed in earlier studies, with a plateau above about 0.5 ppm. These samples are taken mid-season, so may not correlate to soil B taken at other points in the season. But this does indicate that at lower concentrations, soil B helps with S uptake, until the concentration is high enough to have no effect.

Between irrigated and rainfed parts of the fields, there is a lot of overlap with positive correlations between tissue nutrients, indicating that under any healthy uptake conditions, essential plant nutrients are taken up together. This may also explain why Al has only positive correlations with other tissue nutrients, as it is not an essential nutrient but may be taken up as a positive cation regardless with other nutrients. Overall, the only obvious relationship with concentrations and irrigation is K and needs better understanding of year-to-year variations. Both B and Na appear to be related to nutrient availability, although the mechanism could be overall soil health, organic matter mineralization, soil porosity or some other factor not well understood.

Conclusions

This study is observational in nature and designed to observe what research projects can be pursued for Delaware farmers related to fertility and irrigation combinations. The known issues with K uptake under variable moisture conditions (rainfed) are well known (Karlen et al., 1982; Fernadez et al., 2008; Wijewardana at al., 2019), and show some potential here. Although soybean tissue levels of K did not vary between rainfed and irrigated parts of the field, soil concentrations did. One potential explanation is that blanket potash applications continue to raise the levels of K in dry corners, while yields and uptake are lower in drought years. Higher remaining K in the fields may help with K uptake under dry conditions.

It is not clear why NO_3 is higher in rainfed parts of the fields as well since leachable anions like B and SO_4 was similar. We could hypothesize that NO_3 remains due to reduced uptake, but that does not explain why so many other soil nutrients were similar. The higher Na observed in irrigated part of the field could be related to salt additions from irrigation water. This would also explain the higher Na observed in soybean leaf tissue under irrigated conditions. The only other soybean leaf tissue nutrients with observable differences were N and P, which were both higher under reduced stress irrigated parts of the field.

Concentrations of B in the soil had positive influences on many soybean tissue nutrients under both rainfed and irrigated conditions but had negative relationships between tissue B tissue macronutrients. This may indicate that conditions giving rise to higher B concentrations are influencing nutrient uptake or plant health, but higher B in the tissue is not related to this same phenomenon. In particular, B up to about 0.5ppm may assist with S uptake into the soybean plant, with a plateau about that point. Tissue Na concentrations were also negatively influenced by soil B concentrations, but only had a positive relationship with tissue B under rainfed conditions. Boron in the soil can be tied to organic matter mineralization which we wouldn't expect to be similar between rainfed and irrigated parts of the field. Also, NO_3 was different by soil moisture contents, but B was not. This certainly warrants further study.

Higher tissue Na levels had negative relationships with macronutrients under rainfed conditions, another potential indicator of stress. Particularly since higher soil Na had positive relationships with many of these same nutrients. It is obvious that complicated relationships between nutrient uptake and environmental conditions exist, making fertility studies difficult under varying soil moisture.

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