Comparison between sources of potassium for corn, soybean, and wheat production

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2017 Research Summary Points

- Field trials were established at five locations to determine the impact that long-term K application as potassium chloride (KCl) has on corn, soybean, or hard-red spring wheat production in Minnesota.
- Application of K or Cl increased their respective nutrient concentration in plant leaf samples collected at reproductive growth stages. The impact of K_2SO_4 was similar compared to KCl for increasing leaf K concentration and a similar effect was found comparing $CaCl_2$ versus KCl considering leaf Cl concentration.
- Corn grain yield was not significant impacted by Cl, but was increased by K at one of three locations (Lamberton).
- The yield of hard red spring wheat was decreased at one of two locations when $CaCl_2$ was applied versus KCl or K_2SO_4, which did not differ from the control.
- Soybean grain yield was not affected by K application at any of the five locations. The application of Cl decreased yield at one of five locations.
- Yield increase due to the application of K were not likely as most sites tested high (>160 ppm) in soil test K.
- Soybean or wheat grain quality were not impacted greatly by the application of K or Cl.
- Additional years of research are needed at the locations to determine how Cl builds up over time. Fall soil samples showed clear increases in soil Cl at most locations except for Morris which was uncharacteristically wet towards the end of the growing season.

Introduction

Potassium is one of three major macro-nutrients that are required for crops grown in Minnesota. Like phosphorus, potassium availability can be determined for crops using soil tests. The majority of fertilizer potassium is applied to soils in Minnesota as KCl (potassium chloride) which contain equal amounts of potassium and chloride by mass. Chloride is considered a micronutrient and can be beneficial to some crops such as hard red spring wheat. Corn is not known to respond positively or negatively to chloride application.

Over application of chloride has been shown to reduce the yield of soybean (Parker et al., 1983). Reductions have typically been of concern in areas of the United States where chloride has been shown to build over time. Since Cl exists in the soil as a negative cation it can be leached. The relative leaching rate would be greatest for sandy soils and less for clayey soils.

Potassium removal by soybean grain can be substantial necessitating the application of fertilizer K in Minnesota. Substantial amounts of chloride are applied but have not been considered to be detrimental to soybean. Long- and short-term potassium studies conducted in Minnesota have periodically shown significant decreases in soybean grain yield and grain protein concentration with increasing rates of K (Kaiser, unpublished data). The negative impacts of the application of K could be a result of Cl buildup in the soil from KCl repeatedly applied over time. The impacts on soybean were greatest when KCl was applied the fall or spring prior to soybean while application of before the previous crop did not reduce yield. Research is needed to identify if Cl does have a negative impact on soybean yield and quality and what factors may influence a negative response to Cl.

Data on chloride response in hard red spring wheat is scarce in Minnesota. The need for K for hard red spring wheat is relatively low compared to corn or soybean. Thus, KCl had not always been routinely applied in some fields possibly increasing the need to Cl to be applied. Data is needed to update current guidelines for hard red spring wheat for Cl application.

Goals and Objectives

The primary objective of this study is to determine if routine application of removal based rates of K as KCl can lead to a buildup of Cl in poorly drained soils in Minnesota. Two separate studies will be utilized for this work. The first study will be a long-term potassium study established at three locations in 2009 which has focused on K applied as KCl. The second study will be a new long-term trial comparing sources of K applied in a two-year rotation. Specific objectives addressed for this study are:

1. Evaluate critical soil test K levels utilizing long-term K trials.
2. Compare soil test potassium analysis on air dried versus field moist soils.
3. Evaluate the impacts of K fertilizer rate and timing on soybean quality.
4. Determine if Cl will carry-over on poorly drained soils.

5. Compare KCl and K_2SO_4 for supplying K to soybean.
6. Determine if Cl impacts corn, soybean, or hard red spring wheat yield and soybean grain quality.
7. Determine if time of K or Cl application within a 2-year crop rotation affects corn, soybean, or spring wheat response to K or Cl.

Reference Cited

Parker, M.B., G.J. Gascho, and T.P. Gaines. 1983. Chloride toxicity of soybeans grown on Atlantic Coast Flatwoods soils. Agron. J. 75:439:443.

Materials and Methods

Studies were established at four locations (Crookston, Lamberton, Morris, and Waseca). A summary of chemical soil test properties is given in Table 1 for samples collected in spring prior to initial treatment application. Two year cropping rotations will be established at each site where both crops are grown each year. A two-year corn-soybean rotation was established at Lamberton, Morris, and Waseca. A two year hard red spring wheat-soybean rotation was used at Morris and Crookston. Morris was the only location where two separate rotations were established and were managed as separate trials. Plot size was 15' wide at Lamberton, Morris, and Waseca and 11' at Crookston and 30-35' long.

Table 1 Summary of soil test data collected in spring 2017. Samples were collected from the 0-6 and 6-24" depths and are a composite of 8 separate cores collected from each main block.

		Sample	Soil Test†					Cl‡	
Location	Soil Type	Depth	P	K	pH	OM	CEC§	Avg	StDev
		inches	--ppm--			-%-	meq/100g	-----ppm------	
Crookston	Wheatville	0-6"	11	124	8.1	2.9	28.6	5.0	0.9
		6-24"	--	--	--	--	--	2.5	2.2
Lamberton	Amiret	0-6"	7	131	5.0	3.5	12.6	4.2	0.9
		6-24"	--	--	--	--	--	2.8	0.6
Morris C/SB	Forman	0-6"	7	195	7.6	4.7	33.3	2.1	0.7
		6-24"	--	--	--	--	--	2.1	0.6
Morris W/Sb	Forman	0-6"	4	168	7.7	4.3	32.0	3.4	1.0
		6-24"	--	--	--	--	--	3.0	0.7
Waseca	Webster	0-6"	5	146	6.0	4.2	20.0	3.7	0.9
		6-24"	--	--	--	--	--	2.2	0.4

† P, Olsen phosphorus; K, ammonium acetate K; pH, soil pH; OM, organic matter.
‡ Average (AVG) and standard deviation (StDev) for the soil Cl extraction
§ Soil cation exchange capacity measured by cation summation.

Treatments area a combination of fertilizer rate, timing, and source. Fertilizer rate applied was either 100 or 200 lb K_2O applied as KCl or K_2SO_4 (potassium sulfate) or 80 or 160 lbs Cl per acre as $CaCl_2$ (calcium chloride). The $CaCl_2$ rate supplies an identical amount of Cl as applied in the KCl treatment. Due to a calculation error the amount of $CaCl_2$ applied provided 20% more Cl than the target application rates. Lastly, the fourth source included a non-fertilized control. Timing consists of fertilizer applied before soybean or before wheat or corn. A split plot design will be used where main plots will consist of a factorial combination of rate and time while the sub-plots will consist of fertilizer source (none, KCl, K_2SO_4, and $CaCl_2$). Sulfur will be applied as gypsum to balance out S applied in the K sulfate treatment so that the amount of sulfur is equal across all plots. Corn and wheat will receive suggested rates of N and P. Soybean plots will receive P as needed based on soil test results. The 2017 growing season was the establishment year so only half of the plots received fertilizer treatments. The full treatment structure will be established prior to the 2018 growing season.

Soil samples were at 0-6, and 6-24" depths from all main blocks (16 total samples) before the initial treatment application. The 0-6" samples were sieved and split where half was kept in a field moist state and the remaining dried to compare moist K samples to air dried tests. Top soil samples were analyzed for Olsen-P, pH, soil organic matter via loss on ignition, cation exchange capacity (summation method), Cl, Ca, Mg, and Base saturation. The 6-24" depth was only analyzed for Cl.

During Fall 2017, soil samples were collected from all plots receiving the split-plot fertilizer treatments while main blocks which received fertilizer treatments for 2018 were sampled as a whole prior to treatment application. Sampling depths for Fall samples were 0-6 and 6-24" depth. All Fall samples were air dried and the shallow samples were analyzed for K and Cl while the deep samples were analyzed for Cl only. Total Cl in the top two feet was calculated by multiplying ppm Cl in the soil by 8 (assuming 8.000,000 lbs soil at 2' depth).

Leaf tissue samples were collected mid-season. For corn the leaf opposite and below the ear was sampled at R1, wheat flag leaf samples were collected at anthesis, and the newest fully developed soybean trifoliate was sampled at the R1 growth stage. Soybean and wheat grain samples were analyzed for protein content (and soybean was analyzed for oil content) using NIR. Wheat protein values are reported at 12% moisture content which soybean protein and oil is reported at 13%. Grain yield was measured on all plots and yield was adjusted to 15.5% moisture for corn and 13% for soybean and hard red spring wheat.

Statistical analysis was conducted using SAS version 9.3. Analysis was conducted using PROC GLIMMIX assuming fixed effects of fertilizer source, timing, and rate, and random blocking effects. Interactions were assessed using the SLICE option in the LSMEANS statement. All effects are considered significant at the $P \leq 0.10$ probability level.

Results and Discussion

Table 2 Summarizes total monthly precipitation at each location based on data collected by weather stations maintained by the research and outreach centers. Potential impacts of rainfall will be further discussed in the later sections of this report as they pertain to various effects at individual locaitons.

Table 2. Summary of monthly total precipitation for 2017 by location.

Location	May	June	July	August	September
			Inches		
Crookston	0.85	3.61	0.51	1.01	4.01
Lamberton	5.98	2.70	4.01	4.92	2.12
Morris	3.83	3.78	0.92	9.12	4.33
Waseca	5.10	4.16	6.56	3.90	2.02

Initial Soil Test Values

A summary of initial soil test values is given in Table 1. All locations tested high (<120 ppm K) according to current Minnesota guidelines. The lowest two sites were Crookston and Lamberton which the two Morris locations had the highest soil test K concentrations of all sites. Soil test Cl was also measured but there currently is no interpretations for what is a low or high value. Soil Cl concentration was roughly similar among the sites and there was very little variation within each location at the start of the trial. Base saturation was also measured among K, Mg, and Ca but the data are not presented in this report. The base saturation will be assessed at the end of the study to determine if the K application changed the K base saturation at each site.

Effects on Leaf K Concentration

Funding was provided from the Minnesota Soybean Research and Promotion Council to assess treatment impacts on leaf K concentration. A summary for soybean, corn, and spring wheat leaf K concentrations are given in Tables 3, 4, and 5, respectively. Soybean data in Table 3 indicate K application increased trifoliate K concentration at four of the five locations. In most cases the application of K at KCl or K_2SO_4 increased K concentration over the control except for the Morris W/Sb site where there was no difference between the control and K treatments. At both Morris locations, the $CaCl_2$ treatment resulted in the least amount of K in the leaf tissue relative to the other treatments, even less than the control. There were significant timing effects at three of the five locations and a significant time by source interaction at four of five locations which indicated that the K effects only differed among sources for the before soybean application. Since 2017 was the setup year for the study only plots going to soybean had K treatments applied for the soybean crop. It would not be expected for the sources to differ for the application before wheat or corn since only gypsum was applied to those plots during the establishment year. The 2018 growing season will be the first where effects of residual K application will be measured. The lack of an effect of rate was not surprising due to the setup of the experiment. Since the control was included as a sub-plot within each rate by time combination if 100 lbs K_2O was sufficient to increase K concentration there likely would be no effect of rate and the impact of K would be assessed with the source variable. Any impacts of rate of K will likely show up in the rate by source interaction as only two of the source treatments contain K. In the case of the soybean data, only the Crookston location exhibited any effects of K rate for the two K sources applied.

For corn (Table 4), K sources affected leaf K concentration at all three locations. The timing- and rate by source interactions were significant for all three locations indicating an effect for source only for timings where K was applied ahead of the corn and for rate only for sources which contained K. There was on case, at Waseca, where the three-way interaction was significant. The three-way interaction was a likely results of significant rate effects for the KCl and K_2SO_4 sources applied ahead of corn. Similar to the soybean plots, K sources were only applied for plots going into corn so there would be no expected difference in K concentration for the leaf tissue in the before soybean blocks since those treatments were not applied until after the corn crop. Considering the sources, at Lamberton both K sources increase leaf K concentration but the K_2SO_4 increased concentration more than KCl. At Morris, both K sources increased K concentration similarly. At Waseca, the two K sources and $CaCl_2$ had similar K concentration values in the leaf tissue. For wheat, leaf K concentration only varied at Crookston with KCl averaging the greatest K concentration of any source (Table 5).

Effects on Soybean, Corn, and Spring Wheat Yield

A summary of treatment effects on soybean grain yield is given in Table 6. Source only impacted soybean yield at Waseca where yield where the KCl treatment produced less yield than the control, $CaCl_2$, or K_2SO_4 treatments. Crookoston was the only other location were the soybean yield trended less for Cl treatments but the effect failed to reach statistical significance due to relatively low yield for that location. The time by source interaction which occurred at Waseca was due to the source effect only being significant for plots where treatments were applied ahead of the soybean crop. At Lamberton there was a significant effect of time on soybean yield where there was an average of 2 bu/ac less soybean yield produced for the before soybean timing. This indicates there may be some negative impact of source in spite of a lack of significance as indicated by the source main effect and all two-way source interactions. The three-way interaction was significant for Lamberton which may indicate some source effects for specific combination of timing and rate of application. For instance, the 200 lb K_2O rate when KCl was applied yielded 46.5 bushels per acre relative to 51.6 for the 100 lb rate. In other research trials, it has taken a few years of repeated application of KCl to result in reductions in soybean yield so a lack of significant results may be solely an impact of this being the first year of the trials at each location.

For corn, there were increases in corn grain yield at Lamberton from the KCl and K_2SO_4 treatments likely as a results of the K applied (Table 7). At Waseca, both timing and rate main effects did differ but it was not clear why these effects were significant. There were a few areas in the field at Waseca where water ponded and reduced yield. Most of the data from that area was omitted from the analysis but there still was some variation not explained by the treatment effects. There was a significant two-way time by source interaction which occurred at Waseca but analysis of the data indicates differences among sources for the before soybean plots where the sources were not applied. Data from Waseca is inconclusive for any treatment effects.

For wheat, grain yield varied among sources at Crookston but not Morris (Table 8). At Crookston, the source effect was only significant for plots where treatments were applied (before wheat plots). Grain yield trended lower for Cl treated plots and was the lowest for $CaCl_2$ relative to KCl which is interesting since wheat should be more tolerant to Cl application. The field at Morris was planted at a similar time compared to Crookston but field conditions were not ideal for planting which impacted stand establishment and ultimately yield. Yield averages among treatments was highly variable due to stand establishment issues.

Effects on Seed Mass

Seed weights were analyzed for all crops to determine impacts of K and Cl on seed size. Soybean, corn, and wheat data are given in Tables 9, 10, and 11, respectively. Soybean seed weights were only affected by treatments at Crookston and Waseca. At Crookston, the higher rate of fertilizer produced heavier seeds but the impact seemed to be most prevalent only in plots where fertilizer was not applied. Thus, the overall effect at Crookston cannot be attributed to treatments applied for 2017. There was indication for slightly less weight for all treated plots compared to the control at Crookston. At Waseca, the KCl treated plots seed with less weight relative to the control. The K_2SO_4 plots produced seed weights between the control and the KCl treated plots.

For Corn, only fertilizer source impacted seed weight at Morris. Seed weight was greatest for plots with KCl and less when K_2SO_4 was applied ahead of the corn. There were no other effects significant at the other locations. For wheat, fertilizer source affected seed mass at both locations. Seed mass was greatest with $CaCl_2$ at both locations while the KCl treatment increased seed mass to between $CaCl_2$ and the control at the Crookston location. Rate impacted wheat seed weight at Morris with the low fertilizer rate producing, on average, heavier seeds. However, the rate impacts were only significant for treatments receiving Cl at Morris and only for plots where Cl was applied in 2017.

Effects on Seed Quality

Seed quality was assessed only for the soybean (protein and oil) and spring wheat (protein) crops. Protein in soybean grain was affected by fertilizer source at one of the five locations, Crookston (Table 12). At Crookston protein concentration was less when KCl was applied versus the control and the two other fertilizer sources. Time affected grain protein concentration at Crookston, Lamberton, and Waseca. At Crookston, there was a slight reduction in grain protein for the fertilizer application timing before soybean. The time by source interaction was also significant at Crookston but the data indicated a response to source only for the before wheat application timing which had no specific treatment applied. Thus, the data from Crookston is inconclusive as to the impact of the fertilizer treatments on protein. At Lamberton and Waseca, grain protein concentration was greater for the before soybean timing. However, protein concentration was decreased by $CaCl_2$ and KCl applied ahead of the soybean crop compared to similar before wheat application which only included gypsum. At Waseca, the Cl applied appeared to increase protein concentration. The increase at Waseca could have been a result of an inverse relationship between protein and yield which was decreased by Cl. There appeared to be no impacts of fertilizer on soybean grain protein concentration at Morris.

Wheat grain protein data only shows an impact of source on protein concentration at the Morris location (Table 13). Grain protein concentration was slightly higher when Cl was applied relative to K_2SO_4 and the control.

Soybean grain oil concentration was inconsistently impacted by fertilizer treatments (Table 14). Oil concentration varied among the sources at Crookston with the greatest oil concentration for $CaCl_2$ and the least for K_2SO_4. Other effects on oil were relatively minor or could not be readily explained with the statistical analysis. What I am expecting over time is to see greater impacts on quality as additional fertilizer is applied to the same plots. This effect has been seen in studies conducted over a period of 8-10 years in Minnesota. The effect of Cl may be cumulative over time and may take 4-6 years to fully show up in the locations being studied.

Effect on Soil Test Change.

Soil samples were collected from plots at a 0-6 and 6-24" depth in fall prior to fertilizer application for the 2018 growing season. Individual plots were sampled only when fertilizer treatments were applied for the 2017 crop. For blocks where treatments were to be applied for the 2018 crop a single composite soil sample was collected. Data for four of the location is presented in this report. For the Morris corn/soybean, treatments were incorrectly applied ahead of either crop and soil samples thusly were collected from the wrong plots in fall. Due to the misapplication, the corn/soybean site at Morris will be discontinued leaving only the wheat/soybean rotation. Both Morris plots were adjacent to each other such that the soil types are similar and losing one of the studies will not pose a problem for assessing the impacts of the fertilizer sources on soybean yield. Figures summarizing soil test values are organized by 2017 crop.

Figures 1 and 2 summarize the change in soil chloride content at a two-foot depth from spring to fall application for the corn or wheat and soybean plots, respectively. Soil Cl content was greater when either KCl or $CaCl_2$ was applied and in most cases increased from spring to fall with the application of Cl indicating that the element had not leached from the profile. Rate also affected the amount of residual Cl in the profile. Source also varied but the greater impact of $CaCl_2$ was a result of the application rate being 20% greater for $CaCl_2$ versus KCl. The error in the calculation for Cl content of the fertilizer source resulted in an almost 20% greater Cl content in the soil in Fall for $CaCl_2$ versus KCl. Rates of Cl applied at $CaCl_2$ may be adjusted to account for the additional Cl should it be carried over and not flushed out of the soil. Morris was the only location which showed a consistent decrease in soil Cl concentration from Fall to spring and was the site which had the greatest amount of precipitation during 2017. The precipitation at Morris appeared to move Cl deeper in the profile from what was applied with fertilizer prior to the 2017 crop. Crookston showed the greatest increase in Cl and was also the site with the least amount of precipitation. Precipitation was expected to effect the amount of Cl carried over from one year to the next. One item that may be possible further on in this project is to assess the amount of precipitation how it impacts Cl retention in the soil. The amount of Cl retained at the end of the growing season had no clear effect on the yield produced by any crop during 2017.

Soil potassium data is summarized in Figures 3 and 4. Soil test K tended to be greater on average for all treatments in the Fall. This increase is expected as soil K exhibits a wide variation over time. Both treatments that applied K did increase soil K and the increase was also impacted by rate of K applied. There appeared to be no difference for either KCl or K_2SO_4 at increase soil test K. Soil test Ca and Mg were not measured with the Fall 2017 soil samples.

Conclusions

Data indicates that soybean grain yield can be impacted by the source of K applied and that Cl may result in a risk for a decrease in yield. The data from 2017 are only a single year of a multi-year study and it is theorized that the buildup of Cl over time can have a greater impact on soybean grain yield. Corn and wheat yield do not appear to be strongly affected by Cl application. The data summarized provides little conclusive evidence of a large impact of source of potassium on soybean or wheat grain quality. However, it may be possible to build Cl in Minnesota soils over time.

APPENDIX – Tables

Table 3. Summary of main treatment effects on soybean trifoliate K concentration for an average of 30 leaves with petiole sampled as the newest fully developed trifoliate at the R1 (beginning flowering) growth stage at 5 locations in Minnesota. Effects are considered significant at *P*≤0.10.

		Control		$CaCl_2$		KCl		K_2SO_4		Statistical Analysis†						
Location	Timing	100	200	100	200	100	200	100	200	T	R	TxR	S	TxS	RxS	TxRxS
		---%K---								---*P*>F---						
Crookston	W	2.53	2.53	2.44	2.56	2.51	2.50	2.52	2.45	*	0.47	0.71	*	*	0.09	0.23
	Sb	2.56	2.58	2.54	2.56	2.83	2.72	2.61	2.81							
		2.54	2.55	2.49	2.56	2.67	2.61	2.57	2.63							
		2.62b		2.60b		2.72a		2.68ab								
Lamberton	Cn	2.64	2.57	2.83	2.55	2.71	2.52	2.61	2.55	*	0.61	0.58	*	**	0.33	0.37
	Sb	2.62	2.48	2.58	2.51	2.77	2.93	2.74	2.73							
		2.63	2.53	2.71	2.53	2.74	2.73	2.67	2.64							
		2.53b		2.55b		2.69a		2.60b								
Morris C/SB	Cn	2.26	2.31	2.18	2.20	2.31	2.20	2.33	2.28	0.40	0.93	0.07	***	0.10	0.50	0.37
	Sb	2.27	2.29	2.14	2.22	2.40	2.52	2.36	2.45							
		2.26	2.30	2.16	2.21	2.35	2.36	2.35	2.37							
		2.25b		2.15c		2.33a		2.33a								
Morris W/SB	W	2.30	2.02	2.00	1.98	2.10	1.97	2.01	2.22	0.47	0.17	0.69	**	*	0.54	0.40
	Sb	2.03	2.13	1.96	2.06	2.35	2.47	2.36	2.36							
		2.16	2.07	1.98	2.02	2.22	2.22	2.18	2.29							
		2.12a		1.99b		2.23a		2.23a								
Waseca	Cn	2.73	2.69	2.67	2.59	2.63	2.80	2.65	2.66	**	0.83	0.78	0.67	0.16	0.48	0.66
	Sb	2.77	2.77	2.75	2.74	2.82	2.92	2.96	2.86							
		2.75	2.73	2.71	2.67	2.72	2.86	2.81	2.76							
		2.67		2.63		2.69		2.70								

†R, application rate (lb K_2O or Cl per acre); S, fertilizer source; T, time of application in the rotation; x, interaction with.
Asterisks indicate significance at *P*≤0.05 (*), *P*<0.01 (**) and *P*<0.001 probability levels.

Table 4. Summary of main treatment effects on corn leaf K concentration for an average of 15 leaves opposite and below the ear collected at the R1 growth stage at 3 locations in Minnesota. Effects are considered significant at $P \leq 0.10$.

		Control		$CaCl_2$		KCl		K_2SO_4		Statistical Analysis†						
Location	Timing	100	200	100	200	100	200	100	200	T	R	TxR	S	TxS	RxS	TxRxS
		----%K----								----*P*>F----						
Lamberton	Cn	1.69	1.69	1.61	1.57	1.78	1.90	1.86	2.03	0.66	0.11	0.93	***	***	**	0.34
	Sb	1.51	1.60	1.65	1.65	1.65	1.48	1.56	1.74							
		1.60	1.64	1.63	1.61	1.72	1.69	1.71	1.88							
		1.54c		1.59c		1.70b		1.77a								
Morris C/SB	Cn	1.48	1.48	1.4	1.31	1.53	1.78	1.61	1.77	***	0.34	0.27	***	**	**	0.64
	Sb	1.35	1.33	1.43	1.45	1.43	1.36	1.32	1.47							
		1.42	1.40	1.41	1.38	1.48	1.57	1.46	1.62							
		1.33b		1.34b		1.49a		1.48a								
Waseca	Cn	1.88	1.79	2.00	2.00	2.11	2.16	1.90	2.16	*	0.25	0.97	***	***	***	*
	Sb	1.81	1.91	1.89	1.92	1.87	1.81	1.87	1.93							
		1.85	1.85	1.95	1.96	1.99	1.99	1.88	2.05							
		1.89b		1.98a		2.03a		2.02a								

†R, application rate (lb K_2O or Cl per acre); S, fertilizer source; T, time of application in the rotation; x, interaction with.
Asterisks indicate significance at $P \leq 0.05$ (*), $P < 0.01$ (**) and $P < 0.001$ probability levels.

Table 5. Summary of main treatment effects on wheat flag leaf K concentration for an average of 30 leaves collected at anthesis at 2 locations in Minnesota. Effects are considered significant at *P*≤0.10.

		Control		$CaCl_2$		KCl		K_2SO_4		Statistical Analysis†						
Location	Timing	100	200	100	200	100	200	100	200	T	R	TxR	S	TxS	RxS	TxRxS
		----%K----								----*P*>F----						
Crookston	Sb	1.41	1.41	1.42	1.50	1.60	1.65	1.51	1.60	0.65	0.78	0.08	***	***	0.76	0.26
	W	1.52	1.54	1.50	1.47	1.56	1.56	1.55	1.47							
		1.46	1.47	1.46	1.49	1.58	1.60	1.53	1.53							
		1.50c		1.49c		1.59a		1.54b								
Morris W/SB	Sb	1.49	1.60	1.71	1.59	1.70	1.71	1.53	1.60	0.26	0.87	0.83	0.20	0.16	0.09	0.35
	W	1.51	1.63	1.51	1.63	1.51	1.56	1.53	1.57							
		1.50	1.61	1.61	1.61	1.60	1.64	1.53	1.59							
		1.58		1.64		1.66		1.58								

†R, application rate (lb K_2O or Cl per acre); S, fertilizer source; T, time of application in the rotation; x, interaction with.
Asterisks indicate significance at *P*≤0.05 (*), *P*<0.01 (**) and *P*<0.001 probability levels.

Table 3a. Summary of main treatment effects for corn (adjusted to 15.5% moisture) and soybean (adjusted to 13% grain moisture) grain yield at Red Wing, Rochester, Becker, and Lamberton locations during the first crop rotation cycle.

Location	Timing	Control		$CaCl_2$		KCl		K_2SO_4		Statistical Analysis†						
		100	200	100	200	100	200	100	200	T	R	TxR	S	TxS	RxS	TxRxS
		----------------------------bushels per acre @13%-------------------------------								-------------------------*P*>F----------------------------						
Crookston	W	37.4	38.6	38.6	39.5	38.8	41.6	39.1	38.5	0.78	0.58	0.93	0.72	0.13	0.56	0.24
	Sb	40.6	40.1	40.0	38.1	37.8	39.0	39.2	43.6							
		39.0	39.3	39.3	38.8	38.3	40.3	39.1	41.1							
		39.0		39.1		39.3		40.1								
Lamberton	Cn	49.6	53.9	52.3	48.1	50.4	54.0	53.8	53.1	*	0.51	0.10	0.52	0.70	0.92	0.03
	Sb	51.6	47.8	49.0	51.0	51.6	46.5	51.9	49.4							
		50.6	50.8	50.7	49.6	51.0	50.3	52.9	51.3							
		50.7		50.1		50.7		52.1								
Morris C/SB	Cn	50.3	49.7	51.1	53.9	52.2	49.3	47.1	49.2	0.74	0.56	0.41	0.60	0.55	0.96	0.53
	Sb	53.4	50.1	53.1	47	52.9	51.6	51.8	49							
		51.9	49.9	52.1	50.4	52.6	50.5	49.4	49.1							
		50.9		51.3		51.5		49.3								
Morris W/SB	W	36.3	42.3	31.9	45.9	41.0	41.1	45.8	40.5	0.25	0.87	0.34	0.21	0.77	0.25	0.07
	Sb	34.8	35.4	40.5	33.5	34.6	34.6	42.2	38.1							
		35.6	38.8	36.2	39.7	37.8	37.9	44.0	39.3							
		37.2		38.0		37.9		41.7								
Waseca	Cn	61.2	62.7	63.0	61.7	61.6	62.6	62.0	61.3	0.51	0.83	0.77	**	***	0.64	0.15
	Sb	62.8	63.2	62.2	61.8	59.9	60.5	63.3	63.5							
		62.0	63.0	62.6	61.7	60.7	61.5	62.7	62.4							
		63.5a		63.1a		61.8b		63.1a								

†R, application rate (lb K_2O or Cl per acre); S, fertilizer source; T, time of application in the rotation; x, interaction with.
Asterisks indicate significance at $P \leq 0.05$ (*), $P<0.01$ (**) and $P<0.001$ probability levels.

Table 3a. Summary of main treatment effects for corn (adjusted to 15.5% moisture) and soybean (adjusted to 13% grain moisture) grain yield at Red Wing, Rochester, Becker, and Lamberton locations during the first crop rotation cycle.

		Control		$CaCl_2$		KCl		K_2SO_4		Statistical Analysis†						
Location	Timing	100	200	100	200	100	200	100	200	T	R	TxR	S	TxS	RxS	TxRxS
		------------------------------bushels per acre @15.5%--------------------------------								---------------------------*P*>F----------------------------						
Lamberton	Cn	202	205	204	206	209	209	206	208	0.80	0.97	0.71	*	0.90	0.77	0.38
	Sb	201	199	201	197	201	200	200	203							
		202	202	203	201	205	204	203	206							
		200b		199b		206a		202ab								
Morris C/SB	Cn	163	159	168	164	166	164	152	164	0.30	0.79	0.82	0.71	0.95	0.98	0.45
	Sb	164	171	166	160	165	172	167	159							
		164	165	167	162	165	169	160	161							
		164		163		167		161								
Waseca	Cn	204	194	198	197	194	192	200	199	*	*	0.66	0.58	0.06	0.20	0.97
	Sb	205	189	207	205	206	204	201	196							
		205	192	202	200	199	198	200	197							
		199		203		199		199								

†R, application rate (lb K_2O or Cl per acre); S, fertilizer source; T, time of application in the rotation; x, interaction with.
Asterisks indicate significance at $P \leq 0.05$ (*), $P<0.01$ (**) and $P<0.001$ probability levels.

Table 3a. Summary of main treatment effects for corn (adjusted to 15.5% moisture) and soybean (adjusted to 13% grain moisture) grain yield at Red Wing, Rochester, Becker, and Lamberton locations during the first crop rotation cycle.

		Control		$CaCl_2$		KCl		K_2SO_4		Statistical Analysis†						
Location	Timing	100	200	100	200	100	200	100	200	T	R	TxR	S	TxS	RxS	TxRxS
		-----------------------------bushels per acre @13%-------------------------------								--------------------------*P*>F----------------------------						
Crookston	W	105	105	102	102	101	104	104	106	0.78	0.76	0.69	*	**	0.63	0.96
	Sb	104	106	103	107	103	106	103	105							
		105	106	103	104	102	105	104	105							
		106a		103c		104bc		105ab								
Morris W/SB	W	55	68	55	58	67	60	47	55	0.74	0.96	0.29	0.11	0.33	0.96	0.15
	Sb	59	51	60	53	62	70	64	56							
		57	59	57	56	64	65	55	55							
		58		56		65		55								

†R, application rate (lb K_2O or Cl per acre); S, fertilizer source; T, time of application in the rotation; x, interaction with. Asterisks indicate significance at $P \leq 0.05$ (*), $P<0.01$ (**) and $P<0.001$ probability levels.

Table 3a. Summary of main treatment effects for corn (adjusted to 15.5% moisture) and soybean (adjusted to 13% grain moisture) grain yield at Red Wing, Rochester, Becker, and Lamberton locations during the first crop rotation cycle.

		Control		$CaCl_2$		KCl		K_2SO_4		Statistical Analysis†						
Location	Timing	100	200	100	200	100	200	100	200	T	R	TxR	S	TxS	RxS	TxRxS
		----------------------------mg seed^{-1}------------------------------								------------------------*P*>F---------------------------						
Crookston	W	169	167	165	167	161	168	163	169	0.87	*	*	0.13	0.99	0.17	0.08
	Sb	170	175	171	167	169	166	170	169							
		170	171	168	167	165	167	166	169							
		169a		165b		167b		167b								
Lamberton	Cn	148	150	150	147	150	149	149	151	0.94	0.26	0.40	0.22	0.20	0.30	0.12
	Sb	150	151	146	148	146	170	147	146							
		149	151	148	147	148	160	148	149							
		146		147		151		143								
Morris C/SB	Cn	160	161	160	158	163	156	158	161	0.91	0.44	0.85	0.26	0.12	0.09	0.53
	Sb	156	160	160	163	157	157	156	161							
		158	161	160	161	160	157	157	161							
		160		162		160		161								
Morris W/SB	W	154	153	152	152	156	160	157	153	0.15	0.73	0.30	0.32	0.62	0.69	0.32
	Sb	155	157	161	157	158	160	151	158							
		154	155	156	155	157	160	154	155							
		155		156		158		154								
Waseca	Cn	152	153	154	155	154	148	152	152	0.54	0.20	0.42	0.08	0.61	0.16	0.34
	Sb	152	154	153	151	152	151	153	152							
		152	153	153	153	153	150	152	152							
		151a		152a		149b		150ab								

†R, application rate (lb K_2O or Cl per acre); S, fertilizer source; T, time of application in the rotation; x, interaction with.
Asterisks indicate significance at *P*≤0.05 (*), *P*<0.01 (**) and *P*<0.001 probability levels.

Table 3a. Summary of main treatment effects for corn (adjusted to 15.5% moisture) and soybean (adjusted to 13% grain moisture) grain yield at Red Wing, Rochester, Becker, and Lamberton locations during the first crop rotation cycle.

		Control		$CaCl_2$		KCl		K_2SO_4		Statistical Analysis†						
Location	Timing	100	200	100	200	100	200	100	200	T	R	TxR	S	TxS	RxS	TxRxS
		------------------------------ mg seed^{-1} --------------------------------								---------------------------*P*>F-----------------------------						
Lamberton	Cn	265	263	263	262	266	263	261	258	0.13	0.49	0.63	0.33	0.30	0.60	0.35
	Sb	258	252	256	251	256	256	254	258							
		261	257	259	257	261	259	258	258							
		260		258		260		257								
Morris C/SB	Cn	274	266	264	266	261	269	262	266	0.14	0.56	0.89	*	***	0.81	0.17
	Sb	263	269	272	274	280	278	267	270							
		269	267	268	270	270	273	264	268							
		257bc		258ab		261a		254c								
Waseca	Cn	252	243	251	259	249	244	238	253	0.96	0.38	0.81	0.34	0.94	0.40	0.14
	Sb	251	248	245	250	244	255	251	243							
		251	245	248	255	246	250	244	248							
		241		247		241		241								

†R, application rate (lb K_2O or Cl per acre); S, fertilizer source; T, time of application in the rotation; x, interaction with.
Asterisks indicate significance at $P \leq 0.05$ (*), $P < 0.01$ (**) and $P < 0.001$ probability levels.

Table 3a. Summary of main treatment effects for corn (adjusted to 15.5% moisture) and soybean (adjusted to 13% grain moisture) grain yield at Red Wing, Rochester, Becker, and Lamberton locations during the first crop rotation cycle.

		Control		$CaCl_2$		KCl		K_2SO_4		Statistical Analysis†						
Location	Timing	100	200	100	200	100	200	100	200	T	R	TxR	S	TxS	RxS	TxRxS
		mg seed^{-1}								*P*>F						
Crookston	W	30.7	30.6	31.8	31.4	31.6	31.3	31.2	31.1	0.90	0.95	0.90	*	0.06	0.72	0.55
	Sb	31.5	31.3	31.3	31.6	30.7	31.2	30.9	30.4							
		31.1	30.9	31.6	31.5	31.2	31.2	31.0	30.8							
		30.1b		30.7a		30.4ab		30.1b								
Morris W/SB	W	30.8	31.5	32.1	31.0	31.3	30.8	31.3	31.8	0.07	*	0.63	*	*	***	0.09
	Sb	30.9	31.4	31.2	30.8	30.6	31.2	30.9	30.3							
		30.8	31.4	31.7	30.9	30.9	31.0	31.1	31.1							
		30.8b		31.2a		30.8b		30.9b								

†R, application rate (lb K_2O or Cl per acre); S, fertilizer source; T, time of application in the rotation; x, interaction with.
Asterisks indicate significance at $P \leq 0.05$ (*), $P<0.01$ (**) and $P<0.001$ probability levels.

Table 3a. Summary of main treatment effects for corn (adjusted to 15.5% moisture) and soybean (adjusted to 13% grain moisture) grain yield at Red Wing, Rochester, Becker, and Lamberton locations during the first crop rotation cycle.

		Control		$CaCl_2$		KCl		K_2SO_4		Statistical Analysis†						
Location	Timing	100	200	100	200	100	200	100	200	T	R	TxR	S	TxS	RxS	TxRxS
		----------------------------	----------------------------	% Protein @ 13%	----------------------------	----------------------------				-------------------------	-------------------------	-- *P*>F --	-------------------------	-------------------------		
Crookston	W	33.8	33.6	33.9	33.3	33.6	33.1	34.2	33.8	**	0.13	0.54	*	*	0.16	*
	Sb	33.6	33.4	33.4	33.2	33.6	33.0	33.1	33.1							
		33.7	33.5	33.6	33.2	33.6	33.1	33.6	33.5							
		33.6a		33.6a		33.3b		33.6a								
Lamberton	Cn	34.0	34.5	34.2	33.8	34.0	34.1	34.1	34.3	*	0.44	0.32	0.53	*	0.87	0.15
	Sb	34.3	34.2	34.3	35.0	34.4	34.7	34.4	34.3							
		34.1	34.4	34.2	34.4	34.2	34.4	34.3	34.3							
		34.3		34.2		34.4		34.2								
Morris C/SB	Cn	33.9	33.7	34.0	33.6	34.1	33.9	33.8	34.2	0.52	0.83	0.38	0.30	*	0.23	0.55
	Sb	34.0	33.9	34.3	34.3	33.9	33.5	33.9	34.0							
		34.0	33.8	34.1	33.9	34.0	33.7	33.8	34.1							
		33.9		34.2		34.0		34.0								
Morris W/SB	W	33.6	33.9	33.2	34.4	33.9	34.0	34.2	34.2	0.37	0.74	0.40	0.16	0.12	0.07	0.67
	Sb	34.4	33.9	34.6	34.5	33.8	33.7	34.2	33.8							
		34.0	33.9	33.9	34.4	33.8	33.8	34.2	34.0							
		34.2		34.5		34.1		34.5								
Waseca	Cn	34.1	34.0	33.9	34.0	34.2	34.0	33.9	33.8	0.08	0.49	0.96	0.11	0.07	0.25	0.44
	Sb	33.8	34.4	34.4	34.7	34.1	34.2	34.4	34.2							
		33.9	34.2	34.1	34.4	34.2	34.1	34.2	34.0							
		34.0b		34.2a		34.1ab		34.0b								

†R, application rate (lb K_2O or Cl per acre); S, fertilizer source; T, time of application in the rotation; x, interaction with.
Asterisks indicate significance at $P \leq 0.05$ (*), $P<0.01$ (**) and $P<0.001$ probability levels.

Table 3a. Summary of main treatment effects for corn (adjusted to 15.5% moisture) and soybean (adjusted to 13% grain moisture) grain yield at Red Wing, Rochester, Becker, and Lamberton locations during the first crop rotation cycle.

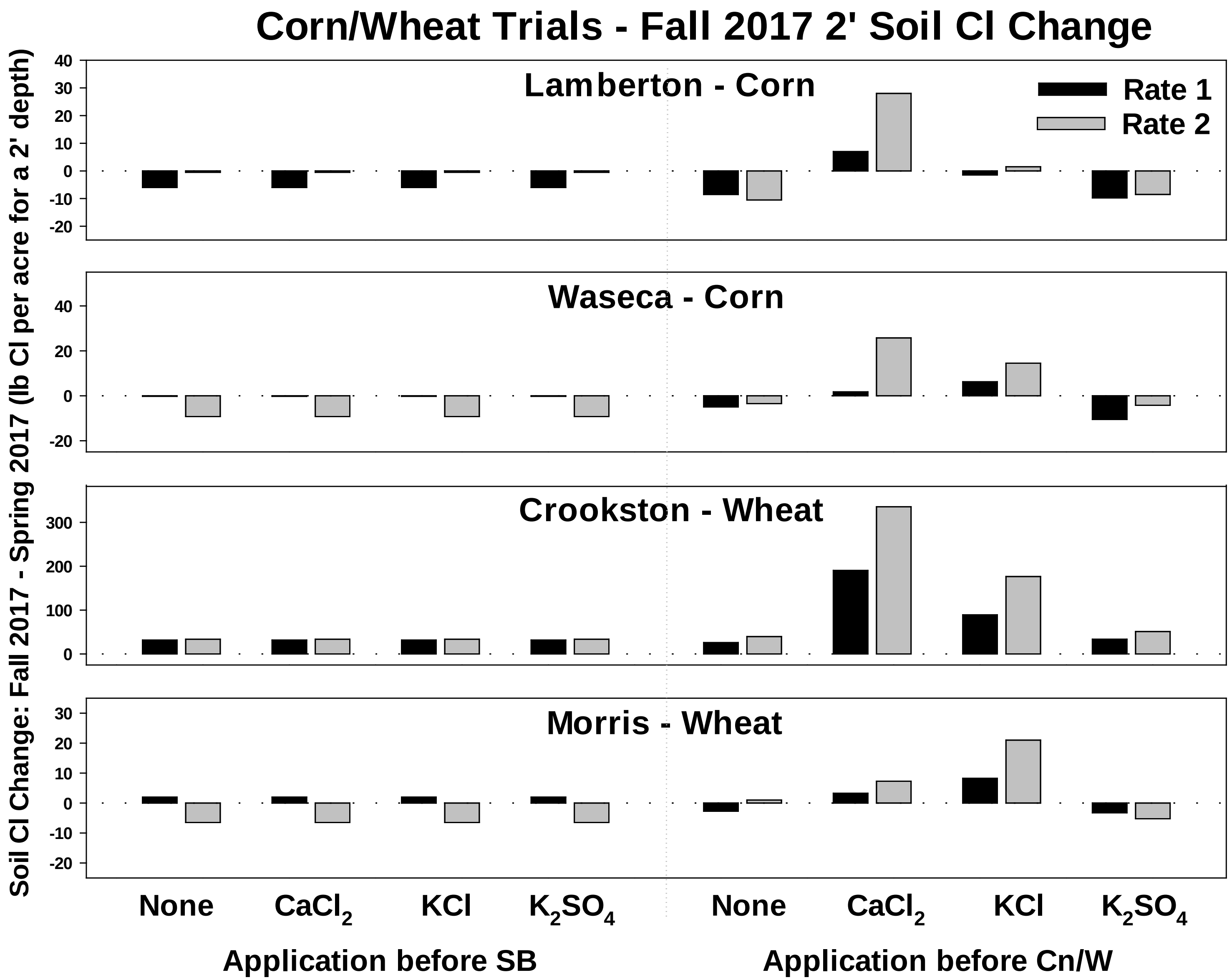
		Control		$CaCl_2$		KCl		K_2SO_4		Statistical Analysis†						
Location	Timing	100	200	100	200	100	200	100	200	T	R	TxR	S	TxS	RxS	TxRxS
		----------------------------- % Protein @ 12%--------------------------------								---------------------------*P*>F-----------------------------						
Crookston	W	17.0	16.9	16.7	16.8	17.2	16.9	16.6	17.1	0.19	0.34	0.62	0.81	0.75	0.61	0.94
	Sb	16.9	16.9	17.0	16.7	16.9	16.9	16.7	17.0							
		16.9	16.9	16.8	16.7	17.0	16.9	16.7	17.0							
		16.9		16.7		16.9		16.8								
Morris W/SB	W	18.0	17.7	17.4	18.2	18.1	18.1	17.8	17.7	0.76	0.94	0.68	0.06	0.07	0.14	0.37
	Sb	18.0	18.1	17.6	18.1	18.0	17.4	17.8	17.1							
		18.0	17.9	17.5	18.1	18.1	17.8	17.8	17.4							
		17.7ab		17.8a		17.8a		17.4b								

†R, application rate (lb K_2O or Cl per acre); S, fertilizer source; T, time of application in the rotation; x, interaction with.
Asterisks indicate significance at $P \leq 0.05$ (*), $P < 0.01$ (**) and $P < 0.001$ probability levels.

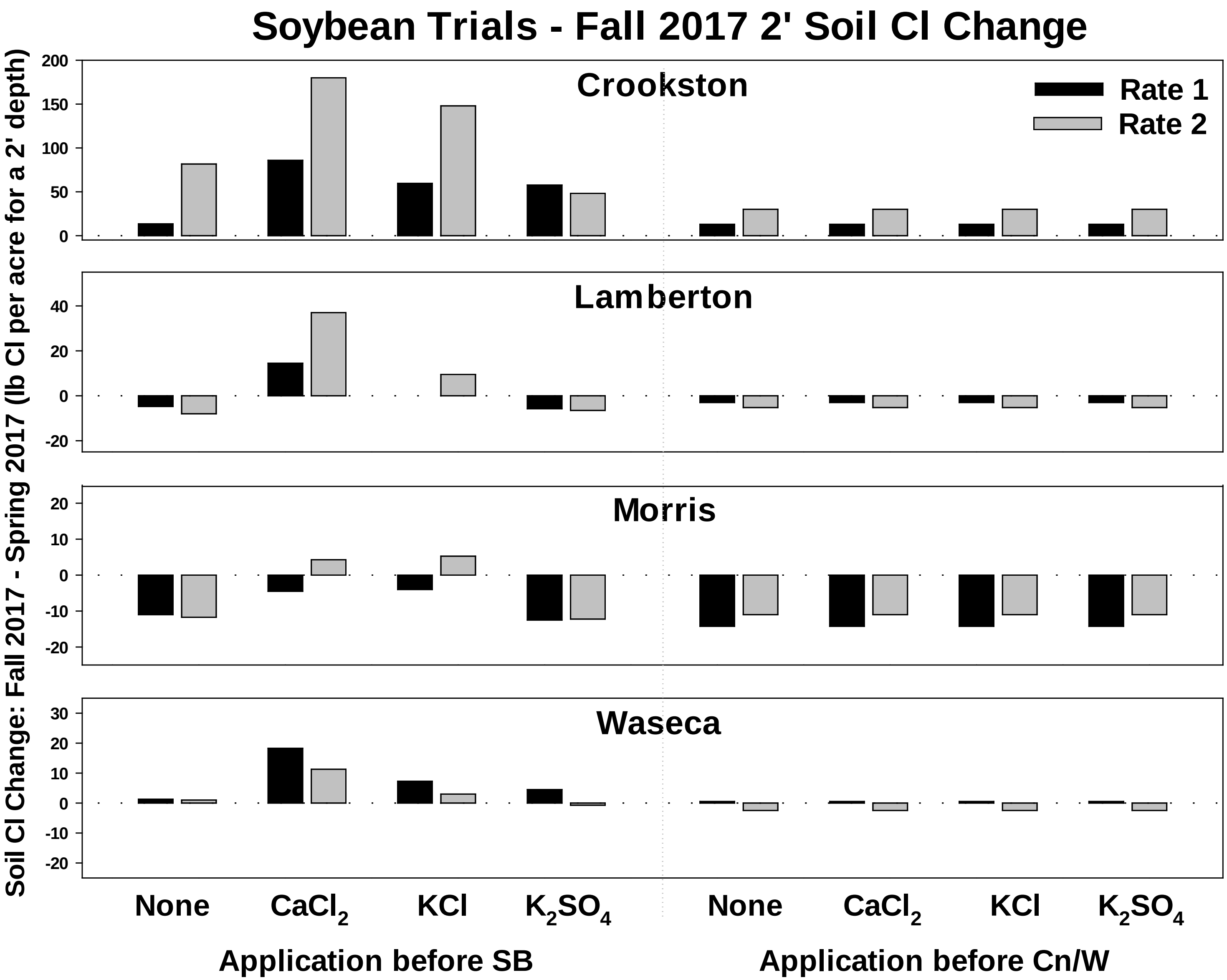
Table 3a. Summary of main treatment effects for corn (adjusted to 15.5% moisture) and soybean (adjusted to 13% grain moisture) grain yield at Red Wing, Rochester, Becker, and Lamberton locations during the first crop rotation cycle.

		Control		$CaCl_2$		KCl		K_2SO_4		Statistical Analysis†						
Location	Timing	100	200	100	200	100	200	100	200	T	R	TxR	S	TxS	RxS	TxRxS
		------------------------------% Oil @ 13%-------------------------------								---------------------------*P*>F-----------------------------						
Crookston	W	16.0	16.1	15.9	16.2	15.9	16.0	15.6	15.9	0.11	**	0.10	**	0.33	**	0.66
	Sb	15.9	16.0	16.1	16.7	15.9	16.4	15.9	15.9							
		16.0	16.1	16.0	16.4	15.9	16.2	15.8	15.9							
		16.1b		16.3a		16.2b		15.9c								
Lamberton	Cn	18.1	17.9	18.0	18.2	18.2	18.1	18.0	17.8	0.61	0.18	0.95	0.16	***	0.38	0.06
	Sb	18.2	18.2	17.9	17.7	17.8	17.7	18.0	17.9							
		18.1	18.0	17.9	18.0	18.0	17.9	18.0	17.9							
		18.1		17.9		17.9		17.9								
Morris C/SB	Cn	18.3	18.3	18.0	18.3	17.9	18.3	18.1	18.3	0.30	0.92	0.99	0.11	**	0.43	0.48
	Sb	18.1	18.2	18.2	18.2	18.2	18.2	17.9	18.0							
		18.2	18.2	18.1	18.3	18.1	18.3	18.0	18.1							
		18.3a		18.2a		18.1ab		18.0b								
Morris W/SB	W	17.7	17.7	18.2	17.6	17.8	17.7	17.4	17.4	0.70	0.75	0.57	0.21	0.07	0.45	*
	Sb	17.8	17.9	17.4	17.6	17.8	17.7	17.5	17.7							
		17.7	17.8	17.8	17.6	17.8	17.7	17.5	17.6							
		17.6		17.6		17.6		17.5								
Waseca	Cn	17.0	17.1	17.5	17.1	17.1	17.0	17.1	17.0	0.77	0.98	0.62	0.46	0.49	0.66	*
	Sb	17.3	17.0	17.0	17.0	17.1	16.9	17.0	17.1							
		17.1	17.0	17.3	17.1	17.1	17.0	17.1	17.0							
		17.2		17.2		17.1		17.1								

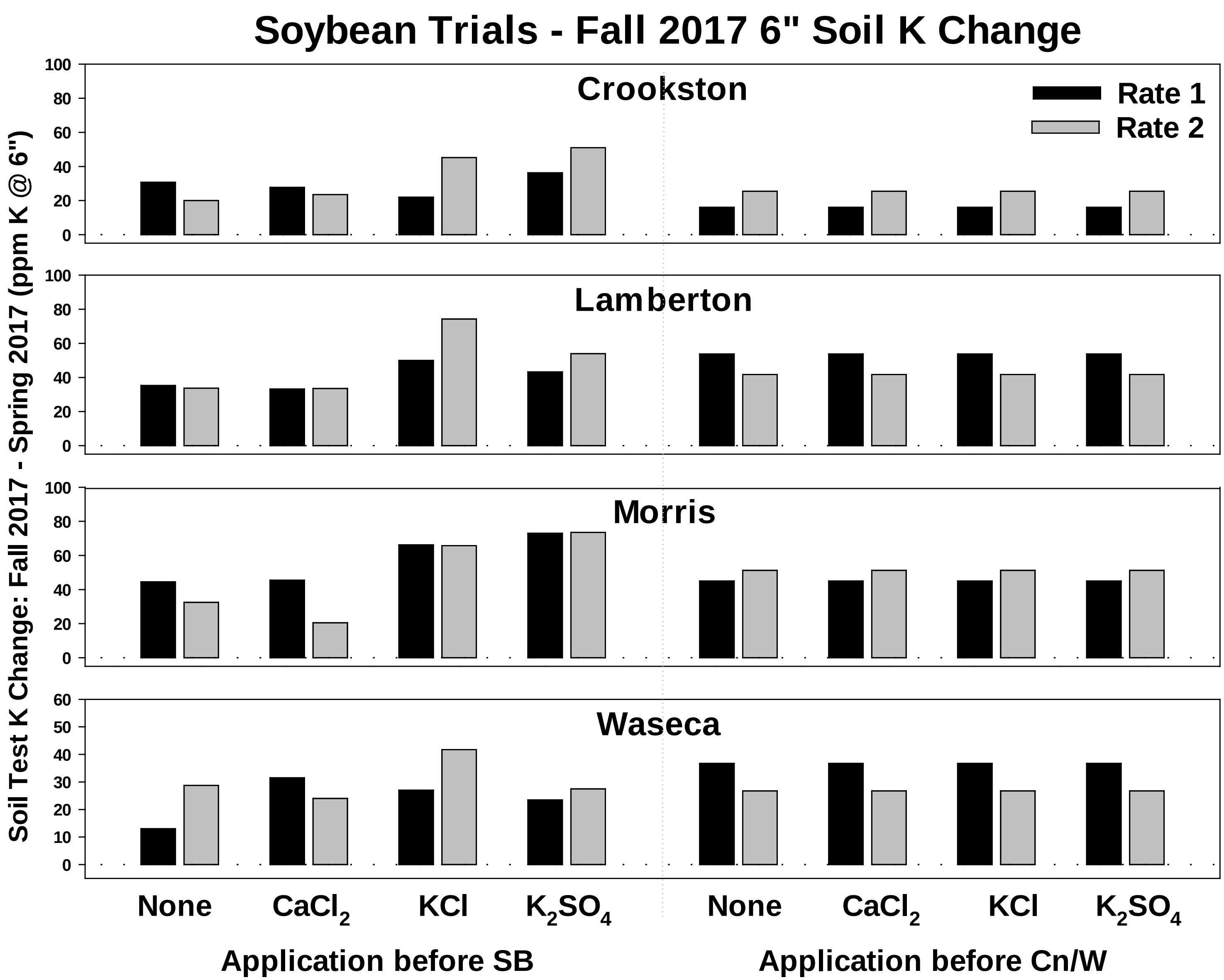
†R, application rate (lb K_2O or Cl per acre); S, fertilizer source; T, time of application in the rotation; x, interaction with.
Asterisks indicate significance at $P \leq 0.05$ (*), $P < 0.01$ (**) and $P < 0.001$ probability levels.



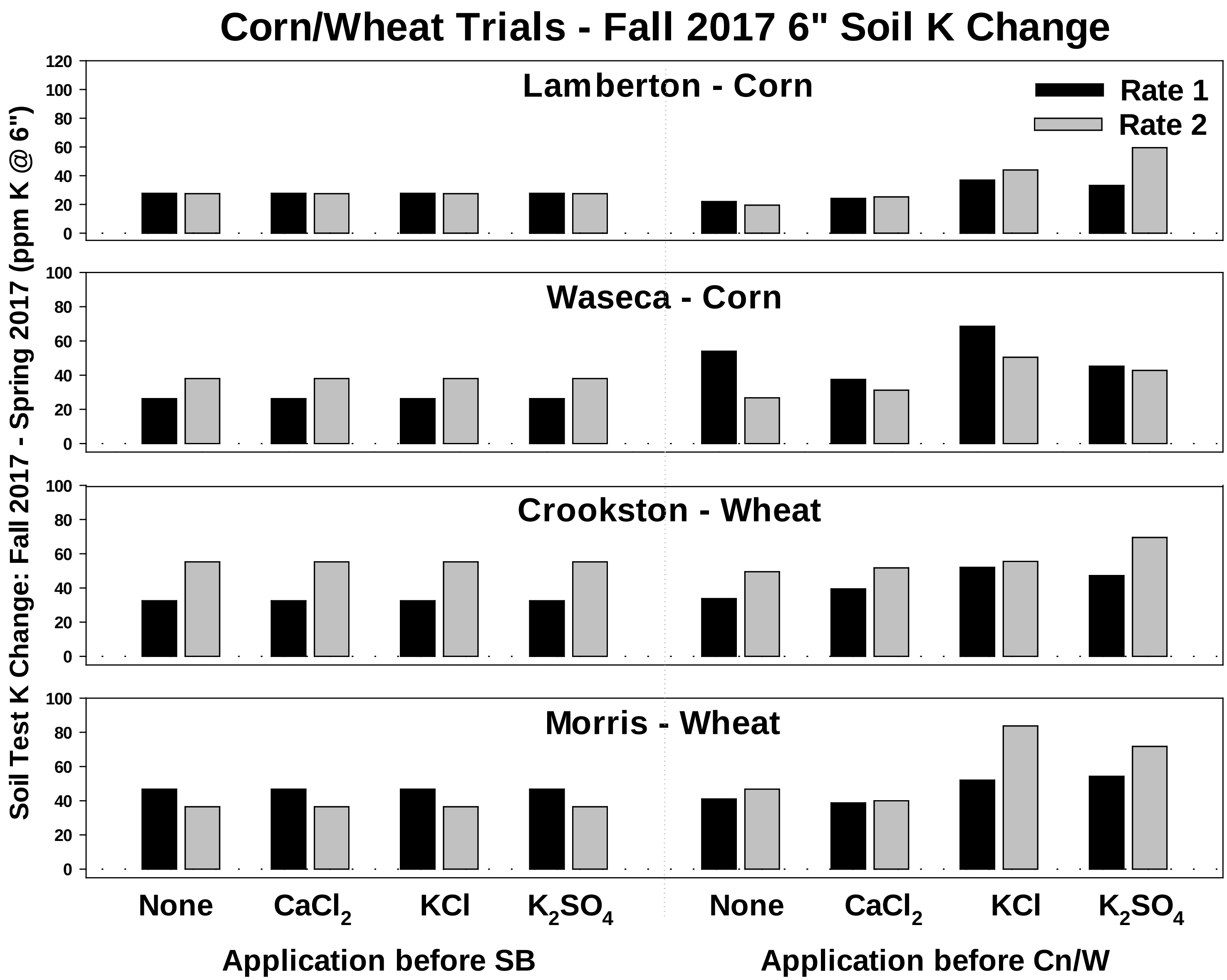
Corn/Wheat Trials - Fall 2017 2' Soil Cl Change
Soil Cl Change: Fall 2017 - Spring 2017 (lb Cl per acre for a 2' depth)
Lamberton - Corn
Rate 1
Rate 2
40
30
20
10
0
-10
-20
Waseca - Corn
40
20
0
-20
Crookston - Wheat
300
200
100
0
Morris - Wheat
30
20
10
0
-10
-20
None
CaCl2
KCl
K2SO4
None
CaCl2
KCl
K2SO4
Application before SB
Application before Cn/W



Soybean Trials - Fall 2017 2' Soil Cl Change
Soil Cl Change: Fall 2017 - Spring 2017 (lb Cl per acre for a 2' depth)
Crookston
Rate 1
Rate 2
200
150
100
50
0
Lamberton
40
20
0
-20
Morris
20
10
0
-10
-20
Waseca
30
20
10
0
-10
-20
None
CaCl2
KCl
K2SO4
None
CaCl2
KCl
K2SO4
Application before SB
Application before Cn/W



Soybean Trials - Fall 2017 6" Soil K Change
Soil Test K Change: Fall 2017 - Spring 2017 (ppm K @ 6")
Crookston
Lamberton
Morris
Waseca
Rate 1
Rate 2
None
CaCl2
KCl
K2SO4
Application before SB
Application before Cn/W



Corn/Wheat Trials - Fall 2017 6" Soil K Change
Soil Test K Change: Fall 2017 - Spring 2017 (ppm K @ 6")
Lamberton - Corn
Waseca - Corn
Crookston - Wheat
Morris - Wheat
Rate 1
Rate 2
0
20
40
60
80
100
120
None
CaCl2
KCl
K2SO4
Application before SB
Application before Cn/W