Nutrient Management for Profitable Soybean Production

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**INTRODUCTION**

The primary source of potassium (K) fertilizer is KCl which contains 50% chloride (Cl) by weight. Soybean yield decreases have been found during recent years and decreased grain protein and increased oil have occurred for soybean within K trials conducted across Minnesota. Purchasing inputs that may reduce the yield of a crop is problematic and Minnesota soybean producers need better fertilizer guidelines to ensure greater profitability of nutrient inputs. Potassium research and improved guidelines are needed as soybean producers are increasingly focusing on inputs to further increase yield across the state, and little guidance is available across the Midwest on maximum rates of potash fertilizer which should be applied to reduce the risk of chloride (Cl) toxicity in soybean. Recent research in Minnesota has demonstrated the need for S to be applied to soybean. Research in the Midwest has indicated that the application of sulfur (S) may mitigate Cl impacts. Additional research would be beneficial to study whether S can help mitigate yield decreases in soybean due to high rates of Cl being applied to further increase yield potential of soybean across the state. The effect of K and Cl on grain quality also must be assessed studying protein, oil, and amino acid distribution as past research in Minnesota has shown that S can increase cysteine and methionine content while K application decreased these two essential amino acids. The proposed research will help better refine potassium and sulfur guidelines for soybean maximizing grain yield and quality parameters.

**PROPOSAL OBJECTIVE & GOAL STATEMENTS:**

Objective

Goals

1) Evaluate the long-term impact of potassium rate and timing in a corn/wheat-soybean rotation on soybean grain yield and quality.

a) Quantify yield effects when K fertilizer is applied at different times and rates in a two-year rotation containing soybean.

b) Quantify changes in soybean protein and oil concentration based on long term K fertilization strategies.

c) Correlate K and Ca or Mg in plant tissue to determine impacts on soybean yield.

2) Determine if the application of Cl has negative effects of soybean grain yield and quality.

 a) Quantify yield impacts for K fertilizer sources applied with and without Cl on soybean varieties that vary in IDC (potentially salt) tolerance.

b) Track rates of Cl buildup in poorly drained soils.

 c) Quantify plant tissue Cl concentration and correlate tissue Cl concentration to the concentration of other essential nutrients.

3) Determine whether sulfur should be considered as an essential nutrient and applied to soybean in Minnesota.

a) Assess the impact of sulfur on soybean grain yield and seed quality.

b) Determine if the application of sulfur can reduce negative impacts of K or Cl on soybean seed quality or seed yield.

c) Further develop a set of sulfur guidelines for soybean production in Minnesota.

**METHODS AND RESULTS**

**Methods:**

*Study 1*

Long term trials were established at four locations in Spring 2017 [Crookston, Lamberton, Morris, and Waseca (Table 1)]. Two-year cropping rotations were established at each site in two blocks, one for each crop. A two-year corn-soybean rotation was established at Lamberton, and Waseca. A two year hard red spring wheat-soybean rotation was established at Morris and Crookston. Treatments are a combination of fertilizer rate, timing, and source. Fertilizer is based on a K application at a K rate of 100 and 200 lbs K2O per acre which is roughly 1 and 2 times expected crop removal for the rotations. Two sources of K, KCl and K2SO4, are compared with a non-fertilized control. An additional source treatment includes CaCl2 (calcium chloride) applied at a rate which supplies an identical amount of Cl as applied in the KCl treatments. The CaCl2 treatment is used to determine if any impacts from KCl may be due to the Cl. Soil Ca content at the beginning of the study will be measured, but the Ca applied is not anticipated to have a significant impact on yield. Gypsum will be applied to balance S applied with the K2SO4 so all plots will receive a relatively high rate of S and Ca annually. Timing will consist of all 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, K2SO4, and CaCl2). The 2019 growing season will represent the beginning of a second two-year cropping rotation.

Soil samples are collected after harvest from all plots sampling from the 0-6 and 6-24” depths. All samples will be air dried and ground prior to analysis. Exchangeable K is determined on the 0-6” samples while Cl will be analyzed on all depths. Exchangeable Ca and Mg was determined on samples collected prior to the 2017 growing season but will not be measured again until after the 2021 growing season after completion of the second rotation. Additional soil samples will be collected in June to be used for soil test K correlation research. June samples will only be taken from the no K plots for each main block (32 per site). June samples will be kept in a field moist state, sieved, and then split where a minimum of 100g of soil is air dried to be analyzed for K while the remaining moist soil is analyzed for K concentration without drying.

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| 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‡ |  K Base Sat. |
| 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 | 1.12 |
|  |  | 6-24" | -- | -- | -- | -- | -- | 2.5 | 2.2 | -- |
| Lamberton | Amiret | 0-6" | 7 | 131 | 5.0 | 3.5 | 12.6 | 4.2 | 0.9 | 2.67 |
|  |  | 6-24" | -- | -- | -- | -- | -- | 2.8 | 0.6 | -- |
| Morris C/SB | Forman | 0-6" | 7 | 195 | 7.6 | 4.7 | 33.3 | 2.1 | 0.7 | 1.71 |
|  | 6-24" | -- | -- | -- | -- | -- | 2.1 | 0.6 | -- |
| Morris W/Sb | Forman | 0-6" | 4 | 168 | 7.7 | 4.3 | 32.0 | 3.4 | 1.0 | 1.37 |
|  | 6-24" | -- | -- | -- | -- | -- | 3.0 | 0.7 | -- |
| Waseca | Webster | 0-6" | 5 | 146 | 6.0 | 4.2 | 20.0 | 3.7 | 0.9 | 1.89 |
|  |  | 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. |  |

Plant tissue samples are collected from all plots and crops. Wheat flag leaf samples are collected at anthesis by sampling 30 plants. Corn leaves opposite and below the ear are sampled at the R1 growth stage. Soybean trifoliate samples are collected at R1 by sampling 25 fully developed trifoliate samples which include leaflets and the petiole. All plant tissue samples are dried, ground, and analyzed for K, Ca, Mg, Cl, NO3-N and NH4-N concentration (NH4 data was discontinued in 2020 and 2021 as the results showed little to no extractable NH4 in the samples). Additionally, grain samples are collected for all crops from all plots, ground, and analyzed for the same elements determined in leaf samples. Soybean and wheat grain will be analyzed for protein concentration and oil will be analyzed on soybean only along with amino acid distribution using NIR.

A second set of trials were established at University of Minnesota Research and Outreach centers at Becker, Morris and Waseca comparing the impact of 0 or 500 lbs of chloride applied per acre as KCl or CaCl2. Varietal sets represented two relative maturities, 1.4 and 1.7 R.M., and varieties that varied in IDC tolerance based on company ratings. Varieties were sourced from Asgrwo and included 14X7, 14X8, 17X7, and 17X8 in 2020. In 2021 Asgrow 13XF0, 14X8, and 17X8 were planted along with Gold Country 1827X. Two varieties were discontinued in 2021 and could not be used. All varieties were seeded at 150,000 seeds per acre in randomly assigned strips across the three fertilizer treatments. Fertilizer sources were applied in the spring within 7 days of planting. Soybean trifoliate samples were collected by sampling the uppermost fully developed trifoliate (leaflets plus petiole) at the R1 growth stage. Grain samples were collected at harvested and analyzed for seed quality parameters as outlines in the long-term trials (seed Cl concentration was not measured).

Study three includes three field studies established at University of Minnesota research centers located at Becker, Lamberton and Morris. A single high-yielding soybean variety will be selected for each location. Three large blocks will be established, replicated four times, where no Cl and either 500 lbs Cl as KCl or CaCl2 will be applied in spring prior to planting. Main blocks will be subdivided into 6 sulfur treatments consisting of two sources, AMS and gypsum, applied at three rates (0, 15, 30 lbs S). Trifoliate samples will be taken at R1 to assess Cl uptake. Trifoliate samples will additionally be analyzed for Total S content by dry combustion. Grain yield, seed weight, and protein, oil, and amino acid distribution will also be measured.

**Summary:**

***Nutrient removal in corn and soybean grain.***

I have continued to track corn and soybean P and K removal. Data are summarized in Table 2. This work started with projects established back in 2009. The removal of P and K has not significantly changed for the two crops the past two years. The summary of this data has been included in the revision of the soybean fertilizer guidelines which was recently updated in January of 2023.

Table 2. Summary of P2O5 and K2O removal for corn and soybean based on data collected from 2008 through 2021 from soil fertility trials across Minnesota reported at 15.5% moisture for corn and 13% for soybean.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Crop | Nutrient | N | Mean | Median | 25% | 75% |
|  |  |  | ----------------------lb. per bushel-------------------- |
| Corn | P2O5 | 10492 | 0.29 | 0.29 | 0.25 | 0.33 |
|  | K2O | 7065 | 0.20 | 0.20 | 0.18 | 0.22 |
| Soybean | P2O5 | 8611 | 0.67 | 0.68 | 0.61 | 0.74 |
|  | K2O | 7134 | 1.09 | 1.10 | 1.04 | 1.15 |

**n, number of samples.**

***Source of potassium in soybean rotations***

Table 3 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 locations.

***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 a low or high value is. 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 initial data are not presented in this report.

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| **Table 3. Summary of monthly total precipitation for by location.** |
| Location | May | June | July | August | September |
|  | Inches |
| 2017 |
| 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 |
| 2018 |
| Crookston | 1.86 | 5.49 | 1.66 | 1.76 | 2.64 |
| Lamberton | 4.58 | 7.99 | 7.29 | 3.53 | 7.19 |
| Morris | 2.28 | 6.40 | 6.92 | 3.67 | 1.92 |
| Waseca | 5.23 | 5.92 | 4.40 | 4.35 | 10.10 |
| 2019 |
| Crookston | 1.79 | 1.69 | 3.19 | 4.54 | 6.72 |
| Lamberton | 4.42 | 2.41 | 6.67 | 2.33 | 6.64 |
| Morris | 4.19 | 4.32 | 4.63 | 5.26 | 6.41 |
| Waseca | 6.26 | 4.68 | 6.44 | 5.43 | 6.57 |
| 2020 |
| Crookston | 1.14 | 4.60 | 7.44 | 3.17 | 0.51 |
| Lamberton | 3.59 | 3.92 | 5.76 | 3.47 | 0.94 |
| Morris | 0.79 | 3.78 | 3.87 | 3.71 | 0.80 |
| Waseca | 4.61 | 6.69 | 5.55 | 6.79 | 2.29 |
| 2021 |
| Crookston | 0.95 | 1.65 | 0.32 | 2.24 | 2.41 |
| Lamberton | 2.74 | 0.49 | 1.17 | 4.75 | 4.98 |
| Morris | 0.94 | 0.82 | 2.13 | 5.06 | 2.53 |
| Waseca | 2.66 | 2.00 | 2.73 | 4.82 | 1.92 |

***Effects on Leaf K and Cl Concentration***

A summary for soybean, corn, and spring wheat leaf K concentrations are given in Tables 4, 5, and 6, respectively. Soybean trifoliate, corn leaf, and wheat flag leaf K concentration was impacted by source at all locations. For soybean and corn, K concentration was increased the most for both sources where K was applied ahead of the crop regardless of the source applied. For soybean, application rate did not impact trifoliate K concentration at three of four locations, and rate impacted wheat leaf K concentration only at Crookston. Two-way interactions were seldom significant for soybean, corn or wheat except for the rate by source interaction which was almost always significant. The rate by source interaction was a result of rate being significant for both sources that contained potassium. The three-way interaction was significant only three of eight times and was a result of K concentration in the plant tissue being greatest when K was applied directly ahead of the crop, for sources containing K at the highest application rate.

The 2021 growing season represented the fifth year of the study. As a result, it is not surprising that K concentrations were greater when K was freshly applied as the plots with a fresh application would have had at least 2 applications compared to the residual plots which only had K applied in 2018. The 2021 growing season represents the completion of two full years for the rotational cycle. However, the application of K will increase K concentration in leaf tissue. The application of CaCl2 never increased leaf K concentration for soybean, but leaf K concentration was slightly higher than the control but not as much as both K sources at both corn locations while wheat tissue K concentration was increased similarly to the K sources when CaCl2 was applied at Morris.

Soybean trifoliate Cl concentration is summarized in Table 7. Corn and wheat Cl data was measured but the data are not included in the report due to similarities in effects compared to the soybean plots at each location. Trifoliate Cl concentration varied among the fertilizer sources at all sites. The time main effect was significant at all locations while the rate main effect was significant at three of four sites. The time by source interaction was always significant along with the three-way time by rate by source interaction. The three-way interaction again indicated that the Cl concentration was greatest when Cl was applied ahead of the soybean crop regardless of source (KCl or CaCl2) and the amount of Cl was increased with increasing Cl application rate.

***Effect on Post Harvest Soil Test Values***

Figures 1 and 2 summarize the change in soil chloride content at a two-foot depth following soybean or corn or wheat from spring 2017 to fall 2021. Conditions have been were relative dry in June and July in 2021 but increased in rainfall in August and September. Most sites showed some elevated soil Cl concentrations for some treatments.

Responses at the sites could generally be lumped into two categories. First, in four cases (Crookston, Lamberton, and Waseca soybean and Waseca corn), the source and time by source interactions were both significant but the three-way interaction was not. Rate generally did not impact soil Cl concentration in all four cases indicating that sources that contained Cl did impact residual Cl concentration but only when applied ahead of the current crop. In the other four cases the three-way interaction was significant which were a result of differences between the two application rates for sources where Cl was applied, and the differences were either only significant or significantly greater when fertilizer was applied ahead of the current crop. These interactions are all expected and show that soil Cl may not build over time. In the case of Waseca soil Cl generally decreases likely due to greater than normal precipitation but the decrease was less where Cl was applied.

Soil potassium data is summarized in Figures 3 and 4. In general, soil test K was increased based on rate of K application and seldom varied between the two sources of K. Differences in sources were generally evident for the high application rate and less for the low application rate which was near crop removal for the two-year rotation. There was generally never a significant decrease in soil test K when the high rate was applied. The plots where K was applied showed higher soil test K with the exception of Waseca. Initial soil samples were taken in spring of 2017 and samples collected in fall can sometimes be a magnitude lower than if sample collection would be delayed to the spring. Waseca is high in clay and the overall reduction in soil test K could be a result of K fixation in the soil. The K might still be present but not in a form that can be extracted by the soil test extraction method used.

***Effects on Soybean, Corn, and Spring Wheat Yield***

A summary of treatment effects on soybean grain yield is given in Table 8. Source impacted soybean yield only at Lamberton and Morris in 2021. Soybean grain yield was less compared to the control for plots were CaCl2 and KCl were applied at Lamberton and were increased by the application of K as K2SO4 at Morris. Yield levels were relatively low at Morris and subsequent analysis of the soil indicated significant soybean cyst nematode pressure at the site, which was not known when the study was established, and a lack of precipitation during the growing season. Time and rate main effects were never significant and neither were any of the two- or the three-way interaction.

For corn, application source varied only at Lamberton (Table 9) corn grain yield was 15 bushels per acre greater when KCl was applied and did not vary among the remaining treatments. There was no other significant effect of note for either corn location in. Wheat yield was affected by fertilizer source at Crookston with greater yield when K was applied regardless of source (Table 10).

***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 11, 12, and 13, respectively. Soybean seed weights were affected by source at Crookston and Waseca (Table 11). At Crookston no treatments differed from the control even though K2SO4 resulted in a lower seed mass than the two Cl sources. At Waseca, both K sources increase seed mass compared to the control and CaCl2. There was no other significant main effect or interaction at any location for soybean seed mass.

For Corn, fertilizer source impacted seed weight at Lamberton and Waseca (Table 12). Seed mass was increased by all fertilizer sources at both sites. Interactions were seldom significant at either corn location. Wheat seed mass was also affected by fertilizer source at both wheat locations (Table 13). At Crookston all fertilizer sources increased seed mass. At Morris, only fertilizers containing Cl increased seed mass. Again, most interactions were not significant for wheat seed mass.

***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 Lamberton, Morris, and Waseca (Table 14). Grain protein concentration was decreased by K at two of the three locations except Waseca where only CaCl2 increased seed protein concentration. The decrease in protein concentration, when it did occur, was similar regardless of K source as indicated by treatment significance. There were no other significant main treatment effects or significant interactions at either Crookston or Lamberton but the timing main effect was significant at Waseca where seed protein concentration was slightly lower when fertilizer was applied in the fall ahead of the soybean crop. Wheat grain protein concentration was not impacted by fertilizer treatments at either location n 2021 (Table 15).

Soybean grain oil concentration affected by fertilizer source at the same locations where protein was affected (Table 16). The effect on seed oil concentration as opposite where oil tended to increase with K application. The inverse effect of protein and oil is common for soybean production.

***Yield data summary across years***

Figures 5 through 6 summarize soybean, corn, and wheat grain yield data averaged across years 2-5. Fertilizer source impacted average soybean yield at all four locations. At Crookston and Lamberton, soybean grain yield was slightly greater with both treatments that applied K while soybean grain yield was less at Morris and Waseca for one or more treatments where Cl was applied. These sets of sites differ in the fact that the control plots tested above the current critical soil test K level, 200 ppm, at Morris and Waseca while soil tests were lower at Crookston and Lamberton in a more responsive soil test range. Time of application varied for soybean yield at Lamberton and Waseca where yield of soybean was less when fertilizer was applied ahead of soybean. Wheat yield was increased by K on average at Crookston regardless of time of application and was not affected by source or timing at Morris. Corn grain yield was affected by source but not timing at Lamberton and source and timing were not significant at Waseca. At Lamberton corn grain yield was actually greatest when KCl was applied and CaCl2 slightly increase yield over the control but not to the degree of KCl. Overall, the data indicates that if K is needed it should be applied as yield will be increased. If K is not needed, then here is a slight risk for a reduction in yield when KCl is applied to soybean. Rate data was not summarized in Figures 5 and 6 as the minimum rate applied should have been, and was, more than the crop needed.

An additional breakdown of crop response to K and S is given in Table 17 averaging data from the 2018 to 2021 growing seasons. The data shows consistent yield increases due to K at 1 of 2 corn or wheat locations, and 3 of the 4 soybean locations. The application of Cl did increase yield of corn on average at Lamberton but decreased soybean yield at Lamberton, Morris, and Waseca. There did not appear to be any significant time by source interactions indicating the source effects were consistent whether the fertilizer was applied ahead of soybean or the rotational crop. This data does indicate that an alternative source of K, such as K2SO4, may benefit soybean. However, K2SO4 is not easily available and costs more than KCl such that an economic analysis should be conducted to determine if switching the source of K applied ahead of soybean. The fact that Cl applied ahead of corn and wheat had no negative effect on yield does indicate that application ahead of these two crops would be preferred over soybean. There was also no overall impact of Rate on yield such that the lowest rate of K or Cl applied had the same impact on yield as the higher rate which is not surprising as the lowest rate was targeted to supply one times the crop removal of K for the rotation.

***Impact on soil K base saturation***

Soybean K base saturation was assessed on the soil samples collected in Fall 2021 after harvest but only on 0-6” sampling depths. Tables 18, 19, and 20 summarize analysis post-harvest after soybean, corn, and wheat, respectively. Fertilizer source consistently impacted K base saturation while application timing and rate affected K base saturation inconsistently. Expectedly, the application of K regardless of source tended to increase K base saturation. The rate by source interaction that was significant almost always, indicated that rate did affect K base saturation when K fertilizer sources were applied. The K base saturation tended to be below 2.0 at most locations except for Lamberton. The 2.0 threshold is typically though of to be where maximum yield is achieved. However, there were instances were sites did respond to K and low rates of applied K were enough to maximize grain yield without achieving the 2.0 threshold. Also, the initial K base saturation at Lamberton was 2.0 at the start of the trial and there still was a response to K for both corn and soybean at the location. While low K base saturation may be indicative of where a response may occur, targeting a specific threshold is not likely needed to ensure maximum yield. It also may not be easy to change K base saturation in a soil if the soil does not have a strong ability or retain K, or the K applied ends up in the non-exchangeable fraction and is not picked up by the soil test.

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| Table 4. 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 4 locations in Minnesota in 2021. Effects are considered significant at *P*<0.10. |
|  |  | Control | CaCl2 | KCl | K2SO4 | Statistical Analysis† |
| Location | Timing | 100 | 200 | 100 | 200 | 100 | 200 | 100 | 200 | T | R | TxR | S | TxS | RxS | TxRxS |
|  |  | ----------------------------------------%K------------------------------------------ | ---------------------------*P*>F----------------------------- |
| Crookston | W | 2.67 | 2.55 | 2.60 | 2.70 | 2.58 | 2.92 | 2.66 | 2.66 | 0.36 | 0.32 | 0.44 | 0.09 | 0.11 | 0.43 | \* |
|  | Sb | 2.47 | 2.58 | 2.43 | 2.54 | 2.64 | 2.70 | 2.83 | 2.79 |  |  |  |  |  |  |  |
|  |  | 2.52b | 2.52b | 2.64a | 2.63ab |  |  |  |  |  |  |  |
| Lamberton | Cn | 2.11 | 2.11 | 2.13 | 2.06 | 2.45 | 2.37 | 2.24 | 2.45 | 0.14 | 0.19 | 0.31 | \*\*\* | 0.16 | 0.07 | 0.12 |
|  | Sb | 2.07 | 2.18 | 1.87 | 2.06 | 2.31 | 2.48 | 2.47 | 2.60 |  |  |  |  |  |  |  |
|  |  | 2.08b | 2.04b | 2.42a | 2.39a |  |  |  |  |  |  |  |
| Morris | W | 1.22 | 1.43 | 1.02 | 1.26 | 1.62 | 1.42 | 1.56 | 1.62 | 0.61 | 0.82 | 0.85 | \*\*\* | 0.87 | 0.96 | 0.21 |
|  | Sb | 1.33 | 1.08 | 1.06 | 1.19 | 1.45 | 1.54 | 1.57 | 1.56 |  |  |  |  |  |  |  |
|  |  | 1.12b | 1.02b | 1.32a | 1.37a |  |  |  |  |  |  |  |
| Waseca | Cn | 2.78 | 2.86 | 2.77 | 2.97 | 2.99 | 3.38 | 3.17 | 3.36 | 0.63 | 0.07 | 0.91 | \*\* | 0.66 | 0.10 | 0.73 |
|  | Sb | 3.06 | 2.85 | 2.77 | 3.13 | 3.20 | 3.42 | 2.99 | 3.22 |  |  |  |  |  |  |  |
|  |  | 2.96b | 2.97b | 3.22a | 3.24a |  |  |  |  |  |  |  |

†R, application rate (lb K2O 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.

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| Table 5. 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 in 2021. Effects are considered significant at *P*<0.10. |
|  |  | Control | CaCl2 | KCl | K2SO4 | Statistical Analysis† |
| Location | Timing | 100 | 200 | 100 | 200 | 100 | 200 | 100 | 200 | T | R | TxR | S | TxS | RxS | TxRxS |
|  |  | ----------------------------------------%K------------------------------------------ | ---------------------------*P*>F----------------------------- |
| Lamberton | Cn | 1.01 | 1.22 | 0.96 | 0.88 | 1.20 | 1.38 | 1.29 | 1.25 | 0.79 | 0.22 | 0.71 | \*\*\* | 0.30 | 0.16 | \* |
|  | Sb | 0.84 | 0.90 | 0.92 | 0.90 | 1.23 | 1.25 | 1.15 | 1.29 |  |  |  |  |  |  |  |
|  |  | 0.99b | 0.91b | 1.31a | 1.22a |  |  |  |  |  |  |  |
| Waseca | Cn | 1.19 | 1.17 | 1.25 | 1.15 | 1.43 | 1.66 | 1.62 | 1.63 | \* | 0.76 | 0.53 | \*\*\* | 0.08 | \* | 0.22 |
|  | Sb | 1.13 | 1.12 | 1.34 | 1.33 | 1.39 | 1.37 | 1.38 | 1.55 |  |  |  |  |  |  |  |
|  |  | 1.17c | 1.26b | 1.49a | 1.53a |  |  |  |  |  |  |  |

†R, application rate (lb K2O 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.

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| Table 6. 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 in 2021. Effects are considered significant at *P*<0.10. |
|  |  | Control | CaCl2 | KCl | K2SO4 | Statistical Analysis† |
| Location | Timing | 100 | 200 | 100 | 200 | 100 | 200 | 100 | 200 | T | R | TxR | S | TxS | RxS | TxRxS |
|  |  | ----------------------------------------%K------------------------------------------ | ---------------------------*P*>F----------------------------- |
| Crookston | W | 1.86 | 2.10 | 1.98 | 2.02 | 2.11 | 2.33 | 2.07 | 2.20 | 0.41 | \* | \* | \*\*\* | 0.68 | 0.57 | 0.78 |
|  | Sb | 1.89 | 1.87 | 2.03 | 2.01 | 2.13 | 2.20 | 2.05 | 2.24 |  |  |  |  |  |  |  |
|  |  | 1.95b | 2.02b | 2.16a | 2.13a |  |  |  |  |  |  |  |
| Morris | W | 1.95 | 1.92 | 1.94 | 1.86 | 2.03 | 2.18 | 1.92 | 2.09 | 0.58 | 0.52 | 0.68 | \*\*\* | 0.14 | \*\*\* | \* |
|  | Sb | 1.86 | 1.95 | 1.97 | 1.97 | 2.02 | 1.94 | 1.89 | 2.08 |  |  |  |  |  |  |  |
|  |  | 1.97b | 1.97b | 2.07a | 2.03a |  |  |  |  |  |  |  |

†R, application rate (lb K2O 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.

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| Table 7. Summary of main treatment effects on soybean trifoliate Cl concentration for an average of 30 leaves with petiole sampled as the newest fully developed trifoliate at the R1 (beginning flowering) growth stage at 4 locations in Minnesota in 2021. Effects are considered significant at *P*<0.10.  |
|  |  | Control | CaCl2 | KCl | K2SO4 | Statistical Analysis† |
| Location | Timing | 100 | 200 | 100 | 200 | 100 | 200 | 100 | 200 | T | R | TxR | S | TxS | RxS | TxRxS |
|  |  | ----------------------------------------ppm Cl------------------------------------------ | ---------------------------*P*>F----------------------------- |
| Crookston | Cn | 865 | 936 | 1112 | 1305 | 1055 | 917 | 920 | 898 | \* | \* | 0.23 | \*\*\* | \*\*\* | \*\* | \*\* |
|  | Sb | 984 | 657 | 1282 | 1844 | 1315 | 1567 | 769 | 989 |  |  |  |  |  |  |  |
|  |  | 929c | 1390a | 1207b | 944c |  |  |  |  |  |  |  |
| Lamberton | Cn | 297 | 307 | 386 | 457 | 350 | 495 | 380 | 299 | \* | \*\* | 0.62 | \*\*\* | \*\*\* | \*\*\* | \* |
|  | Sb | 289 | 360 | 472 | 788 | 471 | 617 | 308 | 311 |  |  |  |  |  |  |  |
|  |  | 286c | 500a | 451b | 285c |  |  |  |  |  |  |  |
| Morris | W | 583 | 637 | 661 | 684 | 661 | 652 | 663 | 663 | \*\* | \* | \* | \*\*\* | \*\*\* | 0.13 | \*\* |
|  | Sb | 622 | 624 | 719 | 914 | 742 | 871 | 611 | 673 |  |  |  |  |  |  |  |
|  |  | 614c | 734a | 726a | 673b |  |  |  |  |  |  |  |
| Waseca | Cn | 199 | 197 | 241 | 286 | 243 | 250 | 193 | 239 | \*\*\* | 0.24 | 0.48 | \*\*\* | \*\*\* | \*\* | \* |
|  | Sb | 223 | 208 | 385 | 544 | 390 | 497 | 214 | 215 |  |  |  |  |  |  |  |
|  |  | 207b | 359a | 346a | 206b |  |  |  |  |  |  |  |

†R, application rate (lb K2O 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.

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| Table 8. Summary of main treatment effects for soybean (adjusted to 13% grain moisture) grain yield at four Minnesota locations in 2021. |
|  |  | Control | CaCl2 | KCl | K2SO4 | 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 | 22.4 | 21.6 | 23.5 | 20.4 | 21.2 | 20.3 | 20.9 | 18.9 | 0.82 | 0.67 | 0.74 | 0.57 | 0.12 | 0.92 | 0.46 |
|  | Sb | 21.2 | 21.0 | 22.3 | 22.8 | 22.6 | 20.7 | 22.5 | 23.3 |  |  |  |  |  |  |  |
|  |  | 21.5 | 22.3 | 21.2 | 21.4 |  |  |  |  |  |  |  |
| Lamberton | Cn | 44.7 | 45.5 | 41.4 | 39.8 | 43.4 | 43.2 | 48.1 | 43.9 | 0.19 | 0.62 | 0.83 | \* | 0.93 | 0.83 | 0.51 |
|  | Sb | 42.8 | 43.6 | 39.8 | 37.6 | 42.2 | 39.5 | 41.2 | 43.4 |  |  |  |  |  |  |  |
|  |  | 44.2a | 39.6b | 42.1ab | 44.1a |  |  |  |  |  |  |  |
| Morris | W | 10.6 | 15.5 | 10.4 | 16.3 | 15.6 | 11.5 | 17.6 | 12.9 | 0.85 | 0.90 | 0.68 | \* | 0.31 | 0.53 | 0.08 |
|  | Sb | 14.9 | 8.5 | 9.6 | 9.7 | 14.2 | 13.2 | 17.2 | 20.3 |  |  |  |  |  |  |  |
|  |  | 12.4b | 11.5b | 13.7b | 17.1a |  |  |  |  |  |  |  |
| Waseca | Cn | 59.3 | 60.4 | 59.4 | 60.6 | 59.2 | 59.8 | 62.2 | 59.0 | 0.18 | 0.58 | 0.33 | 0.71 | 0.99 | 0.38 | 0.76 |
|  | Sb | 55.5 | 60.3 | 58.3 | 59.1 | 55.9 | 59.0 | 58.6 | 59.5 |  |  |  |  |  |  |  |
|  |  | 58.9 | 59.4 | 58.5 | 59.8 |  |  |  |  |  |  |  |

†R, application rate (lb K2O 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.

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| Table 9. Summary of main treatment effects for corn (adjusted to 15.5% moisture) grain yield at two locations in 2021. |
|  |  | Control | CaCl2 | KCl | K2SO4 | 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 | 93 | 96 | 116 | 97 | 113 | 113 | 95 | 112 | 0.33 | 0.96 | 0.92 | 0.06 | 0.91 | 0.39 | 0.29 |
|  | Sb | 93 | 83 | 92 | 96 | 100 | 98 | 92 | 95 |  |  |  |  |  |  |  |
|  |  | 91b | 100ab | 106a | 98ab |  |  |  |  |  |  |  |
| Waseca | Cn | 200 | 184 | 191 | 199 | 191 | 195 | 196 | 202 | 0.10 | 0.73 | 0.66 | 0.15 | 0.99 | 0.12 | 0.13 |
|  | Sb | 202 | 199 | 205 | 205 | 206 | 199 | 209 | 205 |  |  |  |  |  |  |  |
|  |  | 196 | 200 | 198 | 203 |  |  |  |  |  |  |  |

†R, application rate (lb K2O 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.

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| Table 10. Summary of main treatment effects for hard red spring wheat (adjusted to 13% grain moisture) at two locations in 2021. |
|  |  | Control | CaCl2 | KCl | K2SO4 | 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 | 48.7 | 49.3 | 50.8 | 50.5 | 53.4 | 53.7 | 53.8 | 53.7 | 0.74 | 0.32 | 0.33 | \* | 0.68 | 0.85 | 0.91 |
|  | Sb | 49.1 | 53.5 | 50.0 | 54.1 | 49.3 | 56.8 | 51.9 | 56.6 |  |  |  |  |  |  |  |
|  |  | 50.2c | 51.4bc | 53.3ab | 54.0a |  |  |  |  |  |  |  |
| Morris | W | 28.7 | 30.7 | 25.2 | 27.9 | 22.8 | 26.0 | 25.3 | 27.4 | 0.43 | 0.46 | 0.50 | 0.74 | \* | 0.56 | 0.79 |
|  | Sb | 27.1 | 26.3 | 28.6 | 27.1 | 27.4 | 31.3 | 29.3 | 28.2 |  |  |  |  |  |  |  |
|  |  | 28.2 | 27.2 | 26.9 | 27.6 |  |  |  |  |  |  |  |

†R, application rate (lb K2O 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.

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| Table 11. Summary of main treatment effects for soybean seed mass (on a dry basis) for fertilizer sources and rates at five locations in 2021. |
|  |  | Control | CaCl2 | KCl | K2SO4 | 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 | 114 | 115 | 116 | 111 | 115 | 114 | 111 | 111 | 0.76 | 0.57 | 0.80 | 0.09 | 0.15 | \* | 0.30 |
|  | Sb | 114 | 113 | 119 | 115 | 113 | 115 | 112 | 115 |  |  |  |  |  |  |  |
|  |  | 113ab | 115a | 114a | 111b |  |  |  |  |  |  |  |
| Lamberton | Cn | 156 | 158 | 158 | 154 | 155 | 150 | 156 | 154 | 0.51 | 0.58 | 0.26 | 0.26 | 0.82 | 0.44 | 0.88 |
|  | Sb | 152 | 155 | 148 | 151 | 151 | 151 | 150 | 151 |  |  |  |  |  |  |  |
|  |  | 156 | 153 | 153 | 154 |  |  |  |  |  |  |  |
| Morris | W | 170 | 169 | 180 | 178 | 169 | 176 | 178 | 173 | 0.08 | 0.56 | 0.20 | 0.12 | 0.39 | 0.62 | 0.50 |
|  | Sb | 170 | 181 | 179 | 181 | 178 | 182 | 174 | 176 |  |  |  |  |  |  |  |
|  |  | 170 | 176 | 173 | 172 |  |  |  |  |  |  |  |
| Waseca | Cn | 165 | 167 | 164 | 169 | 167 | 165 | 169 | 163 | 0.03 | 0.25 | 0.66 | 0.10 | 0.46 | 0.12 | \*\* |
|  | Sb | 155 | 168 | 164 | 163 | 165 | 163 | 165 | 167 |  |  |  |  |  |  |  |
|  |  | 164c | 165bc | 167ab | 168a |  |  |  |  |  |  |  |

†R, application rate (lb K2O 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.

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| Table 12. Summary of main treatment effects for corn seed mass (on a dry basis) for fertilizer sources and rates at three locations in 2021. |
|  |  | Control | CaCl2 | KCl | K2SO4 | 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 | 192 | 192 | 215 | 204 | 205 | 213 | 195 | 208 | 0.40 | 0.19 | 0.82 | \* | 0.29 | 0.48 | 0.10 |
|  | Sb | 184 | 181 | 181 | 200 | 188 | 200 | 192 | 193 |  |  |  |  |  |  |  |
|  |  | 190b | 201a | 204a | 198ab |  |  |  |  |  |  |  |
| Waseca | Cn | 323 | 296 | 322 | 338 | 305 | 334 | 330 | 314 | 0.66 | 0.78 | 0.95 | 0.06 | 0.15 | \*\* | \*\*\* |
|  | Sb | 305 | 327 | 332 | 306 | 315 | 336 | 323 | 318 |  |  |  |  |  |  |  |
|  |  | 304b | 319a | 316a | 316a |  |  |  |  |  |  |  |

†R, application rate (lb K2O 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.

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| Table 13. Summary of main treatment effects for hard red spring wheat seed mass (on a dry basis) for fertilizer sources and rates at two locations in 2021. |
|  |  | Control | CaCl2 | KCl | K2SO4 | 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 | 26.9 | 26.8 | 27.9 | 27.5 | 27.6 | 27.8 | 27.6 | 28.0 | 0.44 | 0.32 | 0.59 | 0.06 | 0.71 | 0.78 | 0.44 |
|  | Sb | 26.7 | 28.1 | 27.0 | 27.9 | 27.3 | 28.3 | 28.0 | 27.8 |  |  |  |  |  |  |  |
|  |  | 27.2b | 27.7a | 27.8a | 27.8a |  |  |  |  |  |  |  |
| Morris | W | 30.7 | 32.1 | 32.1 | 32.6 | 32.1 | 33.0 | 31.1 | 31.7 | 0.43 | 0.20 | 0.33 | \* | 0.08 | 0.12 | 0.95 |
|  | Sb | 31.6 | 31.9 | 32.4 | 31.9 | 32.2 | 32.2 | 31.2 | 31.2 |  |  |  |  |  |  |  |
|  |  | 31.9b | 32.3a | 32.4a | 31.8b |  |  |  |  |  |  |  |

†R, application rate (lb K2O 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.

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| Table 14. Summary of main treatment effects for soybean seed protein concentration (reported at 13% moisture) for fertilizer sources and rates at five locations in 2021. |
|  |  | Control | CaCl2 | KCl | K2SO4 | 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 | 33.4 | 33.4 | 33.0 | 32.9 | 33.3 | 33.6 | 33.1 | 32.9 | 0.93 | 0.75 | 0.26 | 0.91 | \* | 0.19 | 0.90 |
|  | Sb | 33.2 | 33.1 | 33.2 | 33.0 | 32.7 | 33.2 | 33.4 | 32.9 |  |  |  |  |  |  |  |
|  |  | 33.2 | 33.1 | 33.1 | 33.0 |  |  |  |  |  |  |  |
| Lamberton | Cn | 33.2 | 32.9 | 32.9 | 33.2 | 32.5 | 32.7 | 32.3 | 32.3 | 0.94 | 0.95 | 0.84 | \*\*\* | 0.77 | 0.67 | 0.76 |
|  | Sb | 32.9 | 32.7 | 33.3 | 33.4 | 32.5 | 32.4 | 32.3 | 31.8 |  |  |  |  |  |  |  |
|  |  | 32.9a | 33.2a | 32.6b | 32.3b |  |  |  |  |  |  |  |
| Morris | W | 35.8 | 35.6 | 36.3 | 35.5 | 35.1 | 36.0 | 35.4 | 35.5 | 0.22 | 0.84 | 0.80 | \* | 0.17 | 0.56 | 0.07 |
|  | Sb | 35.8 | 36.9 | 36.7 | 36.7 | 35.2 | 35.6 | 35.5 | 35.4 |  |  |  |  |  |  |  |
|  |  | 36.2a | 36.3a | 35.6b | 35.7b |  |  |  |  |  |  |  |
| Waseca | Cn | 32.1 | 32.1 | 32.3 | 32.9 | 32.8 | 32.0 | 32.0 | 31.6 | \* | 0.71 | 0.12 | \*\* | \*\* | 0.06 | 0.14 |
|  | Sb | 31.5 | 32.4 | 32.3 | 32.4 | 31.5 | 31.1 | 31.2 | 32.0 |  |  |  |  |  |  |  |
|  |  | 31.9b | 32.4a | 31.9b | 31.7b |  |  |  |  |  |  |  |

†R, application rate (lb K2O 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.

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| Table 15. Summary of main treatment effects for hard red spring wheat seed protein concentration (reported at 12% moisture) for fertilizer sources and rates at two locations in 2021. |
|  |  | Control | CaCl2 | KCl | K2SO4 | 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 | 14.5 | 14.6 | 14.5 | 14.7 | 14.8 | 14.8 | 14.5 | 14.6 | 0.58 | 0.80 | 0.19 | 0.38 | 0.72 | 0.86 | 0.87 |
|  | Sb | 14.4 | 14.4 | 14.6 | 14.3 | 14.7 | 14.5 | 14.6 | 14.4 |  |  |  |  |  |  |  |
|  |  | 14.4 | 14.4 | 14.6 | 14.5 |  |  |  |  |  |  |  |
| Morris | W | 15.5 | 15.8 | 15.6 | 15.8 | 15.9 | 15.9 | 16.0 | 15.8 | 0.72 | 0.55 | 0.98 | 0.81 | 0.12 | 0.72 | 0.44 |
|  | Sb | 15.9 | 16.1 | 16.1 | 15.8 | 15.9 | 15.8 | 15.8 | 15.9 |  |  |  |  |  |  |  |
|  |  | 16.2 | 16.2 | 16.3 | 16.3 |  |  |  |  |  |  |  |

†R, application rate (lb K2O 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.

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| Table 16. Summary of main treatment effects for soybean seed oil concentration (reported at 13% moisture) for fertilizer sources and rates at five locations in 2021. |
|  |  | Control | CaCl2 | KCl | K2SO4 | 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 | 17.9 | 17.8 | 17.9 | 18.0 | 17.8 | 17.6 | 18.1 | 17.9 | 0.42 | 0.90 | 0.27 | 0.34 | 0.07 | 0.18 | 0.69 |
|  | Sb | 18.0 | 18.1 | 18.0 | 18.0 | 18.2 | 17.8 | 18.0 | 18.1 |  |  |  |  |  |  |  |
|  |  | 18.0 | 17.9 | 17.9 | 18.0 |  |  |  |  |  |  |  |
| Lamberton | Cn | 18.6 | 18.7 | 18.8 | 18.9 | 18.6 | 18.7 | 18.8 | 19.0 | 0.92 | 0.89 | 0.13 | \* | 0.11 | 0.42 | 0.74 |
|  | Sb | 18.8 | 19.0 | 18.6 | 18.6 | 18.9 | 18.8 | 18.9 | 19.2 |  |  |  |  |  |  |  |
|  |  | 18.8b | 18.7b | 18.7b | 18.9a |  |  |  |  |  |  |  |
| Morris W/SB | W | 16.8 | 17.1 | 16.6 | 17.0 | 17.5 | 17.0 | 17.1 | 17.2 | 0.23 | 0.99 | 0.74 | \*\* | 0.37 | 0.68 | 0.28 |
|  | Sb | 17.3 | 16.4 | 16.2 | 16.5 | 17.1 | 17.0 | 17.2 | 16.9 |  |  |  |  |  |  |  |
|  |  | 16.9bc | 16.6c | 17.2a | 17.1ab |  |  |  |  |  |  |  |
| Waseca | Cn | 18.2 | 18.0 | 18.1 | 17.9 | 17.9 | 18.2 | 18.2 | 18.3 | \*\* | 0.84 | 0.14 | 0.09 | 0.67 | 0.06 | 0.51 |
|  | Sb | 18.4 | 18.1 | 18.2 | 18.0 | 18.3 | 18.5 | 18.7 | 18.1 |  |  |  |  |  |  |  |
|  |  | 18.1ab | 18.0b | 18.2ab | 18.3a |  |  |  |  |  |  |  |

†R, application rate (lb K2O 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.

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| Table 17. Summary of corn, hard red spring wheat, and soybean grain yield data across four growing years (2018-2021) at four locations averaged for fertilizer source main effects across two fertilizer application rates and application timing where fertilizer was applied in the fall directly ahead of the soybean crop or in the fall ahead of the rotational crop. Response to K and Cl is given from results of single degree of freedom contrasts when the contrast indicated a significant effect of K or Cl. Small letters following numbers indicate significance among treatments at the *P*<0.10 probability level. |
|  |  | Source Main Effect | Response to |
| Crop | Location | None | CaCl2 | KCl | K2SO4 | +K | +Cl |
|  |  | --------------------bushels per acre-------------------- |
| Corn | Lamberton | 175c | 176bc | 181a | 179ab | 4.2 | 2.4 |
|  | Waseca | 204 | 206 | 206 | 204 | 0 | 0 |
| Wheat | Crookston | 62b | 62b | 64a | 64a | 1.9 | 0 |
|  | Morris | 36 | 36 | 37 | 36 | 0 | 0 |
| Soybean | Crookston | 38 | 38 | 39 | 39 | 0.7 | 0 |
|  | Lamberton | 52b | 51c | 53bc | 54a | 1.3 | -1.0 |
|  | Morris | 25b | 23c | 26ab | 27a | 2.3 | -1.7 |
|  | Waseca | 67a | 66ab | 65b | 67a | 0 | -0.8 |

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| Table 18. Summary of main treatment effects on % potassium base saturation for post-harvest soil samples collected following soybean at 4 locations in Minnesota in Fall 2021. Effects are considered significant at *P*<0.10. |
|  |  | Control | CaCl2 | KCl | K2SO4 | Statistical Analysis† |
| Location | Timing | 100 | 200 | 100 | 200 | 100 | 200 | 100 | 200 | T | R | TxR | S | TxS | RxS | TxRxS |
|  |  | ----------------------------------------%------------------------------------------ | ---------------------------*P*>F----------------------------- |
| Crookston | W | 1.40 | 1.40 | 1.45 | 1.40 | 1.48 | 1.53 | 1.48 | 1.43 | 0.46 | 0.92 | 0.63 | \* | 0.83 | 0.09 | 0.38 |
|  | Sb | 1.53 | 1.40 | 1.50 | 1.35 | 1.53 | 1.55 | 1.45 | 1.63 |  |  |  |  |  |  |  |
|  |  | 1.55ab | 1.49b | 1.59a | 1.58a |  |  |  |  |  |  |  |
| Lamberton | Cn | 1.93 | 1.70 | 1.80 | 2.00 | 2.18 | 2.38 | 2.08 | 2.50 | \* | 0.07 | 0.21 | \*\*\* | \*\* | \*\* | \* |
|  | Sb | 1.73 | 1.70 | 1.83 | 1.88 | 2.15 | 3.28 | 2.68 | 3.20 |  |  |  |  |  |  |  |
|  |  | 1.84b | 1.86b | 2.51a | 2.67a |  |  |  |  |  |  |  |
| Morris | W | 1.68 | 1.78 | 1.65 | 1.65 | 1.80 | 1.85 | 1.78 | 1.93 | \* | \*\* | 0.58 | \*\*\* | \* | \*\* | 0.57 |
|  | Sb | 1.68 | 1.73 | 1.73 | 1.83 | 1.83 | 2.08 | 1.78 | 2.18 |  |  |  |  |  |  |  |
|  |  | 1.66b | 1.68b | 1.84a | 1.86a |  |  |  |  |  |  |  |
| Waseca | Cn | 1.33 | 1.25 | 1.30 | 1.35 | 1.38 | 1.75 | 1.40 | 1.73 | 0.87 | 0.19 | 0.64 | \*\*\* | 0.66 | \*\*\* | 0.07 |
|  | Sb | 1.25 | 1.28 | 1.25 | 1.33 | 1.38 | 1.90 | 1.48 | 1.58 |  |  |  |  |  |  |  |
|  |  | 1.32b | 1.37b | 1.62a | 1.57a |  |  |  |  |  |  |  |

†R, application rate (lb K2O 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.

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| Table 19. Summary of main treatment effects on % potassium base saturation for post-harvest soil samples collected following corn at 4 locations in Minnesota in Fall 2021. Effects are considered significant at *P*<0.10. |
|  |  | Control | CaCl2 | KCl | K2SO4 | Statistical Analysis† |
| Location | Timing | 100 | 200 | 100 | 200 | 100 | 200 | 100 | 200 | T | R | TxR | S | TxS | RxS | TxRxS |
|  |  | ----------------------------------------%------------------------------------------ | ---------------------------*P*>F----------------------------- |
| Lamberton | Cn | 1.80 | 1.85 | 1.85 | 1.78 | 2.65 | 3.18 | 2.65 | 4.80 | 0.35 | 0.07 | 0.69 | \*\*\* | \* | \* | 0.49 |
|  | Sb | 1.73 | 1.78 | 1.83 | 1.75 | 2.33 | 2.90 | 2.08 | 2.70 |  |  |  |  |  |  |  |
|  |  | 2.67b | 2.43b | 3.42a | 3.64a |  |  |  |  |  |  |  |
| Waseca | Cn | 1.38 | 1.43 | 1.45 | 1.48 | 1.75 | 1.75 | 1.43 | 1.88 | 0.12 | 0.12 | 0.95 | \*\*\* | 0.09 | 0.06 | \*\*\* |
|  | Sb | 1.40 | 1.38 | 1.43 | 1.50 | 1.48 | 1.73 | 1.53 | 1.48 |  |  |  |  |  |  |  |
|  |  | 1.45c | 1.43c | 1.69a | 1.59b |  |  |  |  |  |  |  |

†R, application rate (lb K2O 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.

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| Table 20. Summary of main treatment effects on % potassium base saturation for post-harvest soil samples collected following hard red spring wheat at 4 locations in Minnesota in Fall 2021. Effects are considered significant at *P*<0.10. |
|  |  | Control | CaCl2 | KCl | K2SO4 | Statistical Analysis† |
| Location | Timing | 100 | 200 | 100 | 200 | 100 | 200 | 100 | 200 | T | R | TxR | S | TxS | RxS | TxRxS |
|  |  | ----------------------------------------%------------------------------------------ | ---------------------------*P*>F----------------------------- |
| Crookston | W | 0.98 | 1.03 | 1.00 | 1.10 | 1.05 | 1.48 | 1.05 | 1.25 | 0.66 | \* | 0.32 | \*\* | 0.30 | 0.19 | 0.33 |
|  | Sb | 1.00 | 1.05 | 1.03 | 1.10 | 1.08 | 1.25 | 1.05 | 1.15 |  |  |  |  |  |  |  |
|  |  | 1.02c | 1.06bc | 1.20a | 1.10b |  |  |  |  |  |  |  |
| Morris | W | 1.30 | 1.53 | 1.38 | 1.50 | 1.55 | 1.75 | 1.45 | 1.85 | 0.48 | \*\* | 0.55 | \*\*\* | 0.96 | 0.06 | 0.91 |
|  | Sb | 1.48 | 1.43 | 1.45 | 1.43 | 1.68 | 1.78 | 1.60 | 1.78 |  |  |  |  |  |  |  |
|  |  | 1.44b | 1.48b | 1.68a | 1.68a |  |  |  |  |  |  |  |

†R, application rate (lb K2O 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.



Figure 1. Summary of change in soil Cl content at 0-2’ for soybean locations in fall 2021



Figure 2 Summary of change in soil Cl content at 0-2’ for corn and wheat locations in fall 2021



Figure 3. Summary of change in soil K concentration at 0-6” for soybean locations in fall 2021.



Figure 4. Summary of change in soil K concentration at 0-6” for corn and wheat locations in fall 2021.

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Figure 5. Summary of source and timing main effects on soybean grain yield for each location averaged across the 2018 through 2021 growing season.

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| --- | --- |
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|  |  |

Figure 6. Summary of source and timing main effects on corn and hard red spring wheat grain yield for each location averaged across the 2018 through 2021 growing season.

|  |  |
| --- | --- |
|  |  |
|  |  |
|  |  |
| Figure 7. Summary of source and timing main effects on soybean and hard red spring wheat grain protein concentration for each location averaged across the 2018 through 2021 growing season. |

**Study 2: Varietal response to source of chloride**

 Initial soil test values from the six trial locations are summarized in Table 21. Sites were selected to represent different regions in Minnesota. Becker was an irrigated sand which Cl should be readily leached. However, analysis of irrigation water from the well at Becker found roughly 30 mg L-1 of Cl and a substantial amount of Cl was applied through the irrigation water on an annual basis (Table 22). The site at Morris was selected based on past data showing a small yield decrease from the application of KCl to soybean. Morris also had the highest starting soil Cl concentration of any of the locations (Table 21). Waseca is located in SC Minnesota and has high clay soils that should build Cl but annual precipitation should be enough to move some of the Cl in the soil profile. A summary of monthly total precipitation is given in Table 23.

Results for the ANOVA from the second trial are summarized in Table 24. The varietal main effect is not summarized as there was usually a significant difference in all measured variable among the four varieties but seldom a difference in how treatments impacted them (no significant interaction between variety and fertilizer source). Exceptions to this will be noted. The fact that there was seldom a varietal interaction is not surprising as most of the company data on the varieties used indicates no tolerance to Cl. In fact, most if not all varieties grown in Northern climates are not known to be chloride excluders. It does not appear much emphasis is placed on Cl tolerance for northern varieties as it is assumed the Cl will leach from the soil and not be a problem. Results from Study 1 show the contrary were small but significant yield decreases were found at the majority of the soybean sites with Cl applied in the fall or spring directly ahead of the soybean crop.

 Soybean trifoliate Cl concentration was almost always impacted by Cl source. The exception was Morris 2020 but the lack of a response at Morris in 2020 was due to substantial in-site variation in trifoliate Cl concentration. In fact, the P value was very close to the accepted probability level. There was no difference in how Cl from KCl or CaCl2 impacted soybean trifoliate Cl concentration apart from Becker in 2021 where CaCl2 increased trifoliate Cl concentration more than KCl. There was also a significant variety by source interaction at Becker in 2021. Stand was an issue for some of the strip at Becker in 2021 with poor stand in specific varieties. While a direct link between Cl and emergence could not be made it is likely that the difference in Cl uptake was a result of differences in emergence among the varieties. However, from all the data it is clear that if Cl is applied the soybean plant will take it up regardless of the variety grown.

Soybean grain yield was affected by Cl source at five of six locations. The only exception was Becker in 2020 where variety and the variety by source interaction differed but not source alone. The variety by source interaction because of varietal differences only with the control and KCl treatments and did not indicate specific source effects within only specific varieties. As a whole, soybean grain yield decreased regardless of the source of Cl applied. Morris in 2021 was an exception where KCl did not differ from the control or CaCl2 but the CaCl2 treatments resulted in less yield compared to the control. A summary of data for each year is given in Table 26. Yield data for 2020 is separated for Becker and Waseca versus data for Morris due to the greater impact that treatments had on yield at Morris. Yield was always decreased by the addition of Cl and in most cases was 2-6 bushels per acre which is greater than decreases observed in the long-term trial discussed above. The yield decreases were much greater at Morris in 2020 ranging from 18-19 bushels to the acre. What is interesting is the general lack of visual differences in growth at Morris in spite of the large decreases. It should be noted that the rate of Cl applied, 500 lbs per acre, is larger than what is typically applied but the high application rate was needed to ensure problems would arise.

 Soybean seed mass and seed protein and oil concentration data are given in Table 25. Seed mass was decreased with the addition of Cl at three of six locations. The number of soybean seeds per acre were also evaluated but the data are not presented. When analyzed across locations, seed yield decreases appeared to be a combination of both reduced seed size and fewer seeds per acre. However, seed per acre varied by site and would be more relevant to yield differences within site rather than differences across sites. It is likely that Cl will have a negative impact first on seed size the potentially the number of seeds per acre. Final stand was not evaluated so we do not know whether the Cl reduced stand. All sites were planted at the same initial population with the same planter but that does not mean that there could be differences in germination or effects that may have changed the number of emerged plants per acre which could also impact the number of seeds harvested per acre.

Seed protein concentration was decreased at four of six locations while oil was increased at three of six locations. Effects on soybean grain yield were not translated into changes in seed protein concentration. It is interesting that seed protein concentration was decreased by Cl and not increased due to a decrease in yield possibly shifting resources in the plant like happens with wheat. Seed oil concentration was always increased with the application of Cl.

Graphs showing the relationship between relative yield and trifoliate Cl concentration, seed weight, and seeds per acre, are not given in this article. One issue is that the differences in yield potential across the sites makes it difficult to use the mean of the highest yielding treatment to evaluate relative yield potential for specific plot. In fact, relative yield needs to be calculated individually for all varieties grown at a site to get a better correlation between specific measurements. There was no direct relationship between trifoliate Cl concentration and relative soybean grain yield. However, the data does show that Cl concentration is increased, and yield decreased with Cl application. A specific critical level at which seed yield would be decreased could not be determined from this data and if the value could be generated it may vary from site to site depending on how Cl is retained in the soil. I will continue to look at the data moving forward but there is significant variation in the Cl concentration in the trifoliate leaves for the control plots comparing all the locations. I similarly looked at seed mass and the number of seeds harvested per acre where there was some relationship between seed mass and seed number and soybean grain yield.

What can be concluded is that the impact on soybean grain yield is Cl and not K since CaCl2 had a similar impact on yield as KCl. I have found that K can decrease seed protein concentration and that the impact is from K. This study will not be continued in 2022. More work should be done to look at whether any northern varieties can be Cl excluders. It is currently suggested that no more than 100 lbs of actual KCl is applied ahead of soybean to reduce the potential for a reduction in seed yield. Other data has shown that K can be applied ahead of other crops and still benefits soybean.

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| Table 21. Summary of soil test data collected in spring 2020 and 2021 for six different field locations where two sources of chloride fertilizer were compared to a control. Samples were collected from the 0-6 and 6-24” depths and are a composite of 8 separate cores collected from each main block. |
|  |  | Date of |  | 0-6” Soil Test† |  Cl |
| Year | Location | Fert Ap. | Planting | Soil Type | P | K | pH | OM | 0-6” | 6-24” |
|  |  |  |  |  | --ppm-- |  | -%- | -----ppm------ |
| 2020 | Becker | 14-May | 15-May | Hubbard | 105 | 152 | 6.9 | 2.2 | 14.9 | 12.8 |
|  | Morris | 11-May | 11-May | Tara | 30 | 140 | 6.7 | 4.3 | 26.4 | 28.3 |
|  | Waseca | 13-May | 13-May | Webster | 12 | 159 | 6.1 | 5.0 | 15.6 | 15.9 |
| 2021 | Becker | 7-May | 7-May | Hubbard | 93 | 130 | 6.8 | 2.0 | 10.5 | 8.8 |
|  | Morris | 6-May | 11-May | Tara | 98 | 139 | 7.7 | 4.6 | 45.0 | 23.7 |
|  | Waseca | 5-May | 7-May | Webster | 7 | 156 | 6.0 | 5.5 | 10.2 | 9.1 |
| † P, Bray-P1 phosphorus; K, ammonium acetate K; pH, soil pH; OM, organic matter; Cl, soil chloride extracted with 0.1*M* CaCl2. |

Table 22. Summary of irrigation totals for field trials at Becker in 2020 and 2021 and the average chloride concentration measured in well water samples collected monthly from May to August.

|  |  |  |
| --- | --- | --- |
|  |  | Chloride |
| Year | Irrigation | Concentration | Amount | Total |
|  | inches | mg L-1 | lb/in water | lb acre-1 |
| 2020 | 9.1 | 32.0 | 7.2 | 65.5 |
| 2021 | 15.7 | 27.4 | 6.2 | 96.8 |

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| --- |
| Table 23. Summary of monthly total precipitation for by location. |
| Location | May | June | July | August | September |
|  | Inches |
| 2020 |
| Becker | 1.37 | 1.46 | 3.88 | 6.10 | 0.82 |
| Lamberton | 3.59 | 3.92 | 5.76 | 3.47 | 0.94 |
| Morris | 0.79 | 3.78 | 3.87 | 3.71 | 0.80 |
| Waseca | 4.61 | 6.69 | 5.55 | 6.79 | 2.29 |
| 2021 |
| Becker | 1.42 | 0.86 | 0.47 | 3.97 | 2.80 |
| Lamberton | 2.74 | 0.49 | 1.17 | 4.75 | 4.98 |
| Morris | 0.94 | 0.82 | 2.13 | 5.06 | 2.53 |
| Waseca | 2.66 | 2.00 | 2.73 | 4.82 | 1.92 |

Table 24. ANOVA summary table for measured variable for study 2, which compares the impact of two sources of Cl applied at 500 lb Cl per acre on four soybean varieties.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Main Effect | R1 Cl | Seed Mass | Pro | Oil | Yield |
|  | -----------------------------------*P*>F----------------------------------- |
|  | Becker 2020 |
| Variety | 0.22 | \*\*\* | \*\*\* | \*\*\* | \*\*\* |
| Cl Source | 0.06 | 0.44 | 0.07 | 0.75 | 0.17 |
| Var.xSource | 0.06 | 0.91 | \* | 0.42 | 0.07 |
|  | Morris 2020 |
| Variety | 0.78 | \*\*\* | \*\* | \*\*\* | \*\*\* |
| Cl Source | 0.13 | \*\*\* | \* | \* | \*\*\* |
| Var.xSource | 0.25 | 0.13 | 0.63 | 0.30 | 0.52 |
|  | Waseca 2020 |
| Variety | 0.44 | \*\*\* | \*\*\* | \*\*\* | \*\*\* |
| Cl Source | \*\*\* | 0.22 | 0.65 | 0.56 | \* |
| Var.xSource | 0.68 | 0.28 | 0.56 | 0.52 | 0.96 |
|  | Becker 2021 |
| Variety | \* | \*\*\* | \*\*\* | \*\*\* | \*\* |
| Cl Source | \* | 0.40 | 0.24 | 0.14 | \*\* |
| Var.xSource | \*\* | 0.94 | 0.36 | 0.81 | 0.17 |
|  | Morris 2021 |
| Variety | 0.06 | \*\*\* | 0.06 | 0.07 | 0.21 |
| Cl Source | \*\* | \*\* | \* | 0.17 | 0.07 |
| Var.xSource | 0.63 | 0.18 | 0.18 | 0.82 | 0.12 |
|  | Waseca 2021 |
| Variety | 0.31 | \*\*\* | 0.11 | \*\*\* | \*\*\* |
| Cl Source | \*\*\* | 0.27 | 0.10 | \* | \*\*\* |
| Var.xSource | 0.35 | 0.20 | 0.29 | 0.16 | 0.18 |

*\*, \*\*, and \*\*\* represent treatment significance at P<0,05, 0,01, and 0,001 probability levels.*

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| Table 25. Summary of soybean seed weight and seed protein and oil concentration (at 13% moisture) averaged across four soybean varieties when 500 lbs of Cl per acre were applied as either KCl or CaCl2. Small letters following numbers indicate significance among treatments at the *P*<0.10 probability level. |
| Year | Location | None | KCl | CaCl2 |
|  |  | --------------------R1 Trifoliate Cl (ppm)-------------------- |
| 2020 | Becker | 701b | 864a | 880a |
|  | Morris | 1358 | 1984 | 1471 |
|  | Waseca | 781b | 1818a | 1896a |
| 2021 | Becker | 1095c | 1820b | 2395a |
|  | Morris | 1212b | 2304a | 2205a |
|  | Waseca | 715b | 2074a | 1912a |
|  |  | ---------------soybean grain yield (bu/ac)--------------- |
| 2020 | Becker | 64.8 | 60.9 | 61.8 |
|  | Morris | 67.7a | 49.5b | 49.5b |
|  | Waseca | 69.4a | 67.0b | 68.4b |
| 2021 | Becker | 56.6a | 52.7b | 52.0b |
|  | Morris | 34.4a | 29.6ab | 26.3b |
|  | Waseca | 46.5a | 42.0b | 39.0b |
|  |  | --------------------seed mass (mg seed-1)-------------------- |
| 2020 | Becker | 171a | 160b | 162b |
|  | Morris | 156a | 135b | 139b |
|  | Waseca | 159 | 155 | 158 |
| 2021 | Becker | 156 | 157 | 157 |
|  | Morris | 141a | 131b | 129b |
|  | Waseca | 150 | 148 | 147 |
|  |  | ---------------seed protein concentration (%)--------------- |
| 2020 | Becker | 37.4a | 36.7b | 36.9ab |
|  | Morris | 35.1a | 33.9b | 34.6a |
|  | Waseca | 34.4 | 34.3 | 34.6 |
| 2021 | Becker | 33.8 | 33.4 | 33.8 |
|  | Morris | 35.0a | 34.4b | 34.5b |
|  | Waseca | 30.9a | 30.2b | 30.5ab |
|  |  | ---------------seed oil concentration (%)--------------- |
| 2020 | Becker | 16.8 | 17.0 | 16.9 |
|  | Morris | 17.5b | 17.8a | 17.8a |
|  | Waseca | 17.9 | 17.9 | 17.8 |
| 2021 | Becker | 18.4 | 18.5 | 18.6 |
|  | Morris | 18.2b | 18.4a | 18.5a |
|  | Waseca | 19.8b | 20.0ab | 20.3a |

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| Table 26. Summary of soybean grain yield data averaged across four soybean varieties when 500 lbs of Cl per acre were applied as either KCl or CaCl2. Small letters following numbers indicate significance among treatments at the *P*<0.10 probability level. |
| Year | Location | None | KCl | CaCl2 |
|  |  | --------------------bushels per acre-------------------- |
| 2020 | Becker, Waseca | 67a | 64b | 65ab |
|  | Morris | 68a | 49b | 50b |
| 2021 | Becker, Morris, Waseca | 45a | 42b | 39b |

**Study 3: Effect of sulfur on soybean yield and on mitigation of negative impacts of Cl on soybean.**

Study 3 follows up on work conducted in study 2. Sulfur is taken up in the sulfate form which is an anion like Cl. One area I wanted to focus on is whether sulfate can reduce the negative impact of Cl on soybean. I will not include any overall conclusions for this part of the research project since 2021 is the first year of the study. A summary of locations and pertinent soil test information for sites is given in Table 27. Locations used were similar to Study 2 except for that Lamberton was substituted for Waseca. Lamberton and Morris were rain-fed sites while Becker was irrigated. A summary of Cl and Sulfate-S concentration in irrigation water is given in Table 28. Irrigation water contained roughly similar concentrations of Cl and Sulfate-S at Becker.

A summary of the ANOVA for measured variables is given in Table 29. Soybean grain yield was reduced by Cl at two of the three locations while S never affected yield, nor did S source or rate interact with Cl. At Lamberton, both Cl sources reduced soybean yield by 6 bushels/ac (Table 30). At Morris the CaCl2 treatment alone reduced soybean grain yield while KCl did not result in soybean yield that differed from the control. I have not run the data across sites and will do that for the 2022 project year report when all six location’s data are available.

Trifoliate S concentration was never affected by S source but was affected by S rate at Morris. However, S rate decreased leaf S concentration at Morris. Chloride application did reduce trifoliate S concentration at Becker with similar effects from either Cl source (Table 31). Trifoliate Cl concentration on the other had was always increased by Cl application (Table 32). At Becker, KCl increased trifoliate S concentration less than CaCl2, but results between eh sources were similar at the other two locations. Trifoliate S concentration was affected by sulfur source at Lamberton where gypsum application tended to reduce the amount of Cl in the trifoliate samples. The Cl by S source interaction was significant at Becker and Morris but the exact reason why is not clear. The S source by rate and the three way interaction was also significant at Lamberton.

Seed protein concentration was affected by Cl application at one of three locations while S source or rate never impacted seed protein concentration (Table 33). In contrast seed oil concentration was impacted by Cl at two of three locations and again S had no impact. Seed cysteine (Table 35) and methionine (Table 36) content, both S containing proteins, were seldom impacted by Cl application or S source or rate of application.

This data is part of a multi-year study. Initial results indicate no benefit of S application to soybean regardless of the source applied and that Cl will reduce soybean grain yield regardless of whether S is applied. There was some impact of S on trifoliate S concentration, but any reductions were not translated into reductions in impacts on seed yield. Multiple years of data will help to fully determine the impact of S on Cl.

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| Table 27. Summary of soil test data collected in spring 2021 from three locations in Minnesota for a study on chloride impacts on soybean with and without sulfur application. Samples were collected from the 0-6 and 6-24” depths and are a composite of 8 separate cores collected from each block. |
|  |  |  |  | Date of | 0-6” Soil Test/1 | Cl | SO4-S |
| Year | Location | Soil Type | Variety/2 | Fert. Ap. | Planting | P | K | pH | OM | 0-6” | 6-24” | 0-6” | 6-24” |
|  |  |  |  |  |  | --ppm-- |  | -%- | -----ppm------ |
| 2021 | Becker | Hubbard | DGS10XT71 | 7-May | 7-May | 117 | 113 | 6.7 | 2.0 | 12.1 | 8.3 | 8.3 | 7.8 |
|  | Lamberton | Normania |  |  |  | 55 | 281 | 7.1 | 4.4 | 10.5 | 11.8 | 11.8 | 12.4 |
|  | Morris | Tara | NKS06T8L | 12-May | 13-May | 5 | 132 | 7.8 | 6.6 | 22.9 | 22.2 | 9.8 | 8.1 |
| /1: P, Bray-P1 phosphorus; K, ammonium acetate K; pH, soil pH; OM, organic matter; Cl, soil chloride extracted with 0.1*M* CaCl2; SO4-S, sulfate-S extracted by mono-calcium phosphate./2: DG, Dyna Gro; NK, Northrup King; |

Table 28. Summary of irrigation totals for field trials at Becker in 2021 and 2022 and the average chloride and sulfate-S concentrations measured in well water samples collected monthly from May to August.

|  |  |  |  |
| --- | --- | --- | --- |
|  |  | Chloride | Sulfate-S |
| Year | Irrigation | Conc | Amount | Total | Conc | Amount | Total |
|  |  | mg L-1 | lb/in | lb/ac | mg L-1 | lb/in | lb/ac |
| 2021 | 15.7 | 27.4 | 6.2 | 96.8 | 27.1 | 6.1 | 95.7 |
| 2022 | 11.6 | 28.0 | 6.3 | 73.1 | 26.2 | 5.9 | 68.4 |

Table 29. Summary of ANOVA results for measured variable for the three locations in Study 3 conducted in 2021.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  |  |  | R1 Trifoliate | Soybean Seed |
| Location | Var | Yield | S | Cl | Pro | Oil | Cys | Met |
|  |  | -----*P*>F----- |
| Becker | Cl | 0.18 | 0.07 | \*\*\* | \*\*\* | \* | 0.25 | 0.16 |
|  | S | 0.83 | 0.28 | 0.34 | 0.82 | 0.47 | 0.67 | 0.65 |
|  | ClxS | 0.11 | \* | \*\*\* | 0.89 | 0.28 | 0.26 | 0.26 |
|  | R | 0.46 | 0.84 | 0.96 | 0.25 | 0.47 | 0.44 | 0.85 |
|  | ClxR | 0.68 | 0.82 | 0.90 | 0.45 | 0.39 | 0.17 | 0.38 |
|  | SxR | 0.98 | 0.08 | 0.43 | 0.23 | 0.30 | 1.00 | 0.85 |
|  | ClxSxR | 0.55 | 0.94 | 0.84 | 0.45 | 0.51 | 0.30 | 0.77 |
|  |  |  |  |  |  |  |  |  |
| Lamberton | Cl | 0.08 | 0.13 | \*\*\* | 0.13 | 0.19 | 0.34 | 0.18 |
|  | S | 0.57 | 0.82 | \* | 0.50 | 0.52 | 0.91 | 0.95 |
|  | ClxS | 0.13 | 0.15 | 0.27 | 0.80 | 0.33 | 0.65 | 0.11 |
|  | R | 0.65 | 0.46 | 0.78 | 0.25 | 0.41 | \* | 0.26 |
|  | ClxR | 0.75 | 0.06 | 0.07 | 0.62 | 0.69 | 0.28 | 0.92 |
|  | SxR | 0.51 | 0.90 | \* | 0.29 | 0.97 | 0.61 | 0.68 |
|  | ClxSxR | 0.39 | 0.64 | \* | 0.89 | 0.84 | 0.70 | 0.70 |
|  |  |  |  |  |  |  |  |  |
| Morris | Cl | \* | 0.37 | \* | 0.27 | 0.06 | 0.09 | 0.06 |
|  | S | 0.93 | 0.15 | 0.66 | 0.23 | 0.16 | 0.15 | 0.27 |
|  | ClxS | 0.87 | 0.12 | 0.07 | \* | 0.09 | \*\* | 0.06 |
|  | R | 0.47 | \* | 0.41 | 0.89 | 0.25 | 0.19 | 1.00 |
|  | ClxR | 0.50 | 0.58 | 0.66 | 0.32 | 0.26 | 0.26 | 0.43 |
|  | SxR | 0.83 | 0.96 | 0.38 | 0.43 | 0.66 | 0.06 | 0.20 |
|  | ClxSxR | 0.25 | 0.81 | 0.74 | 0.54 | 0.36 | 0.14 | 0.80 |

*\*, \*\*, and \*\*\* represent treatment significance at P<0,05, 0,01, and 0,001 probability levels.*

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| Table 30. Summary of the impact of chloride source and sulfur source x rate on soybean grain yield at three Minnesota locations in 2021 |
|  |  | AMS | Gypsum |  |
| Location | Cl Source | 0 | 15 | 30 | 0 | 15 | 30 | Avg |
|  |  | --------------------bushels per acre (13%)-------------------- |
| Becker | None | 56 | 59 | 56 | 64 | 60 | 58 | 59 |
|  | KCl | 57 | 56 | 54 | 53 | 53 | 51 | 54 |
|  | CaCl2 | 51 | 52 | 49 | 48 | 55 | 53 | 51 |
|  | Avg | 54 | 55 |  |
| Lamberton | None | 63 | 66 | 69 | 62 | 63 | 60 | 64a |
|  | KCl | 57 | 59 | 60 | 56 | 57 | 61 | 58b |
|  | CaCl2 | 59 | 54 | 57 | 58 | 61 | 58 | 58b |
|  | Avg | 60 | 60 |  |
| Morris | None | 33 | 24 | 25 | 25 | 28 | 31 | 28a |
|  | KCl | 17 | 23 | 25 | 19 | 21 | 24 | 22a |
|  | CaCl2 | 12 | 13 | 14 | 14 | 10 | 13 | 13b |
|  | Avg | 21 | 21 |  |

|  |
| --- |
| Table 31. Summary of the impact of chloride source and sulfur source x rate on soybean grain yield at three Minnesota locations in 2021 |
|  |  | AMS | Gypsum |  |
| Location | Cl Source | 0 | 15 | 30 | 0 | 15 | 30 | Avg |
|  |  | --------------------R2 Trifoliate S conc. (%)-------------------- |
| Becker | None | 0.34 | 0.34 | 0.34 | 0.35 | 0.35 | 0.33 | 0.34a |
|  | KCl | 0.33 | 0.32 | 0.34 | 0.33 | 0.33 | 0.31 | 0.33b |
|  | CaCl2 | 0.34 | 0.33 | 0.37 | 0.31 | 0.31 | 0.30 | 0.32b |
|  | Avg | 0.34 | 0.32 |  |
| Lamberton | None | 0.29 | 0.30 | 0.27 | 0.29 | 0.28 | 0.28 | 0.29 |
|  | KCl | 0.26 | 0.27 | 0.28 | 0.27 | 0.25 | 0.28 | 0.27 |
|  | CaCl2 | 0.26 | 0.26 | 0.28 | 0.27 | 0.29 | 0.28 | 0.27 |
|  | Avg | 0.28 | 0.28 |  |
| Morris | None | 0.26 | 0.25 | 0.26 | 0.26 | 0.25 | 0.26 | 0.26 |
|  | KCl | 0.30 | 0.29 | 0.28 | 0.28 | 0.27 | 0.26 | 0.28 |
|  | CaCl2 | 0.28 | 0.27 | 0.27 | 0.27 | 0.27 | 0.26 | 0.27 |
|  | Avg | 0.27 | 0.26 |  |

|  |
| --- |
| Table 32. Summary of the impact of chloride source and sulfur source x rate on soybean grain yield at three Minnesota locations in 2021 |
|  |  | AMS | Gypsum |  |
| Location | Cl Source | 0 | 15 | 30 | 0 | 15 | 30 | Avg |
|  |  | -------------------- R2 Trifoliate Cl conc. (ppm)-------------------- |
| Becker | None | 762 | 795 | 812 | 888 | 742 | 800 | 780c |
|  | KCl | 2666 | 3331 | 2867 | 2380 | 2314 | 2611 | 2695b |
|  | CaCl2 | 2010 | 2332 | 2221 | 4939 | 4331 | 4116 | 3325a |
|  | Avg | 2569 | 1977 |  |
| Lamberton | None | 935 | 999 | 1043 | 995 | 905 | 972 | 970b |
|  | KCl | 4099 | 3455 | 3266 | 2512 | 3871 | 2885 | 3348a |
|  | CaCl2 | 4133 | 3321 | 3505 | 3206 | 3088 | 3631 | 3481a |
|  | Avg | 2751a | 2448b |  |
| Morris | None | 1225 | 1217 | 1288 | 1407 | 1038 | 1238 | 1236b |
|  | KCl | 2751 | 2789 | 2685 | 2995 | 3412 | 3050 | 2846a |
|  | CaCl2 | 3494 | 3443 | 3094 | 3397 | 2762 | 3158 | 3225a |
|  | Avg | 2402 | 2469 |  |

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| Table 33. Summary of the impact of chloride source and sulfur source x rate on soybean grain yield at three Minnesota locations in 2021 |
|  |  | AMS | Gypsum |  |
| Location | Cl Source | 0 | 15 | 30 | 0 | 15 | 30 | Avg |
|  |  | --------------------Seed Protein conc. (%)-------------------- |
| Becker | None | 33.1 | 33.2 | 32.4 | 33.1 | 32.9 | 32.9 | 32.9a |
|  | KCl | 32.2 | 31.9 | 31.9 | 32.0 | 31.9 | 32.0 | 32.0b |
|  | CaCl2 | 32.2 | 32.0 | 31.9 | 31.8 | 32.1 | 32.0 | 32.0b |
|  | Avg | 32.3 | 32.3 |  |
| Lamberton | None | 34.2 | 34.2 | 34.3 | 34.1 | 34.0 | 34.4 | 34.2 |
|  | KCl | 34.4 | 34.1 | 34.1 | 34.3 | 34.3 | 34.5 | 34.3 |
|  | CaCl2 | 34.4 | 34.6 | 34.6 | 34.4 | 34.4 | 35.0 | 34.6 |
|  | Avg | 34.3 | 34.4 |  |
| Morris | None | 35.0 | 35.1 | 35.1 | 34.8 | 35.1 | 34.8 | 35.0 |
|  | KCl | 34.2 | 34.2 | 34.2 | 34.6 | 34.8 | 35.3 | 34.6 |
|  | CaCl2 | 35.0 | 35.1 | 34.1 | 35.3 | 35.0 | 35.1 | 34.9 |
|  | Avg | 34.7 | 35.0 |  |

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| Table 34. Summary of the impact of chloride source and sulfur source x rate on soybean grain yield at three Minnesota locations in 2021 |
|  |  | AMS | Gypsum |  |
| Location | Cl Source | 0 | 15 | 30 | 0 | 15 | 30 | Avg |
|  |  | --------------------Seed Oil conc. (%)-------------------- |
| Becker | None | 18.6 | 18.7 | 18.9 | 18.2 | 18.5 | 18.6 | 18.6b |
|  | KCl | 19.1 | 19.3 | 18.8 | 19.1 | 18.9 | 19.1 | 19.0a |
|  | CaCl2 | 19.0 | 19.2 | 19.0 | 19.0 | 19.0 | 19.0 | 19.0a |
|  | Avg | 18.9 | 18.8 |  |
| Lamberton | None | 18.9 | 19.1 | 18.8 | 18.9 | 19.1 | 19.0 | 19.0 |
|  | KCl | 19.1 | 19.2 | 19.1 | 19.0 | 18.9 | 18.9 | 19.0 |
|  | CaCl2 | 19.0 | 18.8 | 18.8 | 18.9 | 18.8 | 18.6 | 18.8 |
|  | Avg | 19.0 | 18.9 |  |
| Morris | None | 17.5 | 17.1 | 17.0 | 17.2 | 17.2 | 17.1 | 17.2b |
|  | KCl | 17.5 | 17.6 | 17.6 | 17.4 | 17.2 | 17.0 | 17.4a |
|  | CaCl2 | 17.2 | 17.2 | 17.3 | 17.1 | 17.3 | 17.2 | 17.2ab |
|  | Avg | 17.3 | 17.2 |  |

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| Table 35. Summary of the impact of chloride source and sulfur source x rate on soybean grain yield at three Minnesota locations in 2021 |
|  |  | AMS | Gypsum |  |
| Location | Cl Source | 0 | 15 | 30 | 0 | 15 | 30 | Avg |
|  |  | ------------------Seed Cysteine conc. (% of total pro.)------------------ |
| Becker | None | 0.59 | 0.56 | 0.57 | 0.59 | 0.59 | 0.56 | 0.58 |
|  | KCl | 0.58 | 0.55 | 0.55 | 0.57 | 0.57 | 0.57 | 0.56 |
|  | CaCl2 | 0.56 | 0.59 | 0.58 | 0.56 | 0.55 | 0.57 | 0.57 |
|  | Avg | 0.57 | 0.57 |  |
| Lamberton | None | 0.57 | 0.60 | 0.59 | 0.57 | 0.58 | 0.60 | 0.58 |
|  | KCl | 0.58 | 0.60 | 0.59 | 0.58 | 0.60 | 0.58 | 0.59 |
|  | CaCl2 | 0.60 | 0.60 | 0.59 | 0.59 | 0.59 | 0.61 | 0.60 |
|  | Avg | 0.59 | 0.59 |  |
| Morris | None | 0.58 | 0.59 | 0.60 | 0.58 | 0.58 | 0.58 | 0.58a |
|  | KCl | 0.56 | 0.57 | 0.57 | 0.57 | 0.57 | 0.59 | 0.57b |
|  | CaCl2 | 0.56 | 0.57 | 0.57 | 0.60 | 0.57 | 0.58 | 0.57b |
|  | Avg | 0.57 | 0.58 |  |

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| Table 36. Summary of the impact of chloride source and sulfur source x rate on soybean grain yield at three Minnesota locations in 2021 |
|  |  | AMS | Gypsum |  |
| Location | Cl Source | 0 | 15 | 30 | 0 | 15 | 30 | Avg |
|  |  | ---------------Seed Methionine conc. (% of total pro.)------------------ |
| Becker | None | 0.54 | 0.54 | 0.53 | 0.54 | 0.54 | 0.54 | 0.54 |
|  | KCl | 0.53 | 0.53 | 0.53 | 0.54 | 0.53 | 0.53 | 0.53 |
|  | CaCl2 | 0.53 | 0.54 | 0.54 | 0.53 | 0.53 | 0.54 | 0.53 |
|  | Avg | 0.53 | 0.53 |  |
| Lamberton | None | 0.54 | 0.55 | 0.54 | 0.53 | 0.54 | 0.55 | 0.54 |
|  | KCl | 0.55 | 0.55 | 0.55 | 0.54 | 0.54 | 0.54 | 0.54 |
|  | CaCl2 | 0.54 | 0.54 | 0.54 | 0.54 | 0.55 | 0.55 | 0.55 |
|  | Avg | 0.54 | 0.54 |  |
| Morris | None | 0.54 | 0.54 | 0.54 | 0.54 | 0.53 | 0.54 | 0.54a |
|  | KCl | 0.53 | 0.53 | 0.52 | 0.53 | 0.53 | 0.54 | 0.53ab |
|  | CaCl2 | 0.53 | 0.54 | 0.53 | 0.54 | 0.54 | 0.54 | 0.52b |
|  | Avg | 0.53 | 0.54 |  |

**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. Corn and wheat yield do not appear to be strongly affected by Cl application from the initial data, but Cl is building in the soil at two of the four locations. When soil test K is in a responsive range, less than 200 ppm, K fertilizer should be applied, and the source of K does not matter for soybean, wheat, or corn. Application of K as little as 80 lbs of Cl per acre can reduce yield and the greatest risk is when K is applied directly ahead of the soybean crop and soil tests indicate a response to K should not occur. The application of K itself can reduce seed protein concentration which is an additional reason to reduce K application ahead of the soybean crop.

Data from the second study does point to the negative impact of Cl on soybean grain yield. High enough rates of Cl can negatively impact both soybean grain yield and seed protein concentration. The plant tissue data from both studies shows that Cl will be taken up by the plant if it is in the soil where it can readily move with soil pore water. Sites do vary in the potential to carry Cl in the soil which also can affect the severity that Cl may have on soybean grain yield reduction. However, irrigated sites like Becker also present a risk as Cl in the irrigation water may compound the impact of Cl applied in fertilizer. While soil test K can be low in irrigated soils it would be better to not apply high rates of KCl ahead of the soybean crop. Other research is looking at optimal rates of K application for soybean and timing of application (fall versus spring). The effect of S on Cl is inconclusive at this time.