Nutrient Management for Profitable Soybean Production

2020-21 Technical Report – Preliminary Nov 2021

Daniel Kaiser -University of Minnesota

**INTRODUCTION**

Interest in potassium (K) fertility in soybean has increased recently. The primary source of potassium 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. The goal of this work is to determine whether Cl applied to soybean may negatively impact soybean grain yield and quality and whether Minnesota soybean farmers need to avoid application of KCl directly ahead of the soybean crop or apply a different source of K fertilizer. Past research has shown yield decreases in single year K fertility trials but long-term trials are more advantageous as the impacts of weather can be assessed at each location on the build-up of Cl in the soil. Grain quality will also be assessed studying protein and oil concentration along with the distribution of amino acids. Further work will study the impacts of macronutrient (P, K, and S) application on the distribution of amino acids in the grain. Past research funded by AFREC has shown that S and K can impact cysteine and methionine content. Funding from the Minnesota soybean growers provided the foundation for the development of a database for specific nutrients to study impacts on amino acid levels in the soybean grain. Past data collected from long term plots will be utilized with newly collected samples to study changes in the distribution of amino acids in the grain following differing fertilization strategies.

Proposal Objective & Goal Statements:

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.

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) Evaluate the impacts of macro-nutrients on the distribution of essential amino acids in soybean grain.

a) Assess the impact of long-term application of P, K, and S on soybean protein and oil content.

b) Assess the effect of various macronutrients (P, K, and S) on amino acid distribution using NIR.

c) Develop a database containing information related to essential nutrients’ impacts on soybean grain quality.

**METHODS AND RESULTS**

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

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

**Methods:** 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 2020 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.

|  |
| --- |
| 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 and NH4 concentration. 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 Dekalb and included 14X7, 14X8, 17X7, and 17X8. 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 were not measured).

**Summary:**

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

Table 1. Summary of P2O5 and K2O removal for corn and soybean based on data collected from 2008 through 2019 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 | 9617 | 0.29 | 0.29 | 0.25 | 0.34 |
|  | K2O | 6474 | 0.20 | 0.20 | 0.18 | 0.22 |
| Soybean | P2O5 | 7436 | 0.67 | 0.69 | 0.62 | 0.74 |
|  | K2O | 6247 | 1.09 | 1.10 | 1.04 | 1.15 |

**n, number of samples.**

I have continued to track corn and soybean P and K removal. Data are summarized in Table 1. 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 completed over the summer of 2020.

***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.

|  |
| --- |
| **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 |

***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 data are not presented in this report.

***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 almost all locations (Crookston soybean and wheat tissue K concentration was not impacted by source). For soybean and corn, K concentration was increased the most for both sources which applied K regardless of the source applied. For soybean, application rate did not impact trifoliate K concentration, but rate impacted corn leaf K concentration at both sites and wheat leaf K was impacted by rate only at Crookston. Two-way interactions were seldom significant for soybean but the time- or rate by source interactions were significant at both corn locations and the time by source interaction was significant at both wheat locations. In both cases, the time by source interaction was a result of a greater increase in trifoliate K concentration when K was applied directly ahead of the crop grown (time by source) or rate affected leaf K only for the treatments where K was applied (rate by source).

The 2020 growing season represented the fourth 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 2020 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 except for Waseca. The time by source interaction was significant at Morris and Waseca, which at Waseca indicated that sources varied but only for the before soybean application timing. The time by source interaction indicates a greater response to newly applied Cl at Morris. The rate by source interaction was also significant at Morris and Waseca as a result of rate impacting Cl uptake only for the sources of fertilizer containing Cl. The three-way interaction was significant at all sites which will require further investigation.

***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 2020. Conditions have been relatively wet at most locations which is evident by a decrease in soil Cl from the initial sampling in the spring of 2017 at some locations, especially Waseca. 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 decrease likely as a result of 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 Morris and Waseca in 2020. Soybean grain yield was less compared to the control for plots were CaCl2 and KCl were applied at Waseca and were increased by the application of K regardless of source 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. The only other significant effect was that of time at Waseca where soybean grain yield was greater when fertilizer was applied ahead of the corn crop.

For corn, application source varied only at Lamberton (Table 9) corn grain yield was 6 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 2020 nor was wheat yield significantly impacted by treatment at either location (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 Lamberton, Morris, and Waseca (Table 11). In all three cases soybean seed mass was slightly less when Cl was applied. 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 (Table 12). Seed mass was increased when KCl was applied at Lamberton, which is similar to what occurred in 2019. There were no significant interactions between timing, source, or rate for corn seed mass at either location. Wheat seed mass was not affected by treatments at either location in 2020 (Table 13).

***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 Crookston, Lamberton, and Waseca (Table 14). Grain protein concentration was decreased by K. The decrease was similar regardless of K source as indicated by treatment significance, but the decrease tended to be slightly greater with K2SO4. There were no other significant main treatment effects or significant interactions at either Crookston of 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. A summary of source and timing impacts across three growing seasons (through 2020) is given in Figure 7. Source affected average seed protein concentration at Crookston and Waseca where seed protein concentration was decreased the greatest under K2SO4, was slightly greater with KCl, and was the greatest and did not differ between CaCl2 and the no fertilizer control. Timing only varied at Crookston where soybean seed protein concentration was greater when fertilizer was applied ahead of wheat. Fertilizer timing did not affect soybean seed protein concentration at the remaining three location.

Wheat grain protein concentration was not impacted by fertilizer treatments at either location n 2020 (Table 15). A three-year summary of wheat protein concentration is also included in Figure 7. Fertilizer source did not impact wheat grain protein concentration at either location. Timing affected wheat grain protein concentration only at Crookston where the before wheat treatment resulted in a slightly greater grain protein concentration. The increase was minimal.

Soybean grain oil concentration was not impacted by fertilizer treatments (Table 16). A three-year summary of soybean seed oil concentration has not been completed at this time but will be completed following the 2020 crop year summary.

***Yield data summary across years***

Figures 5 through 6 summarize soybean, corn, and wheat grain yield data averaged across years 2-4. Year 4 is the 2020 growing season and is included in this report since it will be submitted after the 2020 yield data are collected. 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 was not significant but the yield before corn trended higher at Waseca. Wheat yield was increased by K on average at Crookston and was not affected by source or timing at Morris. Corn grain yield was not affected by source or timing at Lamberton at Waseca. However, the source effect was close to significance at Lamberton. 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 a 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 not 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.

***Varietal response to source of chloride***

 Results from the second trial are summarized in Table 18. The varietal main effect is not summarized as there was usually a significant difference in all measured variable among the four varieties but not difference in how treatments impacted them (no significant interaction between variety and fertilizer source). Yield data for 2020 and 2021 are summarized in Table 18. 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 trifoliate samples were collected from all 2020 plots but due to our lab back log they have not been summarized. With the high rates of Cl applied we should see a similar effect on trifoliate Cl concentration as was found in the long-term study. I will summarize the 2020 data along with the 2021 trifoliate Cl concentration for the final 2021 project year report.

Soybean seed mass and seed protein and oil concentration data are available for the 2020 locations and are given in Table 19. Seed mass was decreased with the addition of Cl at both locations. The number of soybean seed per acre were also evaluated but there was no indication that Cl decreased the number of seed per acre, rather yield was reduced due to a reduction in seed size. Seed protein concentration was decreased by Cl at Becker and Morris and the decreased was greatest with the application of KCl which I consistent with other results showing a negative impact of K on seed protein concentration. See was only affected at Morris where Cl increased oil content likely as a result in the reduction of yield. Seed Cl concentration was not determined as we did not feel it was needed for this study.

**Preliminary 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 2017-2020 represents part 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 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.

|  |
| --- |
| 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 2020. 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 | 2.29 | 2.48 | 2.57 | 2.50 | 2.41 | 2.58 | 2.34 | 2.38 | 0.23 | 0.48 | 0.23 | 0.27 | \* | 0.99 | 0.17 |
|  | Sb | 2.54 | 2.47 | 2.48 | 2.52 | 2.55 | 2.58 | 2.54 | 2.60 |  |  |  |  |  |  |  |
|  |  | 2.19 | 2.25 | 2.25 | 2.18 |  |  |  |  |  |  |  |
| Lamberton | Cn | 2.38 | 2.34 | 2.45 | 2.30 | 2.53 | 2.49 | 2.47 | 2.53 | 0.68 | 0.61 | 0.23 | \*\*\* | 0.46 | 0.17 | 0.09 |
|  | Sb | 2.38 | 2.37 | 2.32 | 2.37 | 2.51 | 2.65 | 2.55 | 2.56 |  |  |  |  |  |  |  |
|  |  | 2.43b | 2.41b | 2.57a | 2.56a |  |  |  |  |  |  |  |
| Morris | W | 1.48  | 1.67  | 1.65  | 1.53  | 1.71  | 1.94  | 1.81  | 1.85  | 0.87 | 0.55 | 0.57 | \*\*\* | \*\* | 0.41 | \* |
|  | Sb | 1.67  | 1.62  | 1.50  | 1.51  | 1.91  | 1.72  | 1.94  | 2.07  |  |  |  |  |  |  |  |
|  |  | 1.61b | 1.54b | 1.83a | 1.89a |  |  |  |  |  |  |  |
| Waseca | Cn | 2.30  | 2.33  | 2.45  | 2.38  | 2.55  | 2.82  | 2.63  | 2.93  | 0.88 | 0.52 | 0.73 | \*\*\* | 0.58 | 0.18 | 0.79 |
|  | Sb | 2.22  | 2.28  | 2.46  | 2.48  | 2.90  | 2.82  | 2.51  | 2.88  |  |  |  |  |  |  |  |
|  |  | 2.24b | 2.31b | 2.70a | 2.61a |  |  |  |  |  |  |  |

†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.

|  |
| --- |
| 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 2020. 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 | 1.54 | 1.49 | 1.61 | 1.68 | 2.06 | 2.29 | 1.87 | 2.23 | 0.23 | \*\* | 0.14 | \*\*\* | \*\* | \*\*\* | 0.69 |
|  | Sb | 1.58 | 1.53 | 1.55 | 1.59 | 1.79 | 2.02 | 1.85 | 2.06 |  |  |  |  |  |  |  |
|  |  | 1.29c | 2.41b | 1.82a | 1.79a |  |  |  |  |  |  |  |
| Waseca | Cn | 1.34 | 1.42 | 1.53 | 1.46 | 1.82 | 2.17 | 1.60 | 1.85 | \*\*\* | \*\* | 0.32 | \*\*\* | \* | \*\* | 0.07 |
|  | Sb | 1.27 | 1.29 | 1.38 | 1.36 | 1.64 | 1.71 | 1.44 | 1.63 |  |  |  |  |  |  |  |
|  |  | 1.37d | 1.47c | 1.84a | 1.65b |  |  |  |  |  |  |  |

†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.

|  |
| --- |
| 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 2020. 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 | 1.47 | 1.56 | 1.51 | 1.69 | 1.61 | 1.66 | 1.55 | 1.62 | 0.31 | \* | 0.62 | 0.15 | \* | 0.88 | 0.09 |
|  | Sb | 1.59 | 1.62 | 1.47 | 1.47 | 1.53 | 1.62 | 1.47 | 1.64 |  |  |  |  |  |  |  |
|  |  | 1.64 | 1.60 | 1.68 | 1.62 |  |  |  |  |  |  |  |
| Morris | W | 0.95 | 0.99 | 1.14 | 1.20 | 1.28 | 1.16 | 1.01 | 1.06 | 0.23 | 0.92 | 0.25 | \* | \*\*\* | 0.79 | 0.56 |
|  | Sb | 1.13 | 1.07 | 1.02 | 0.99 | 0.99 | 1.11 | 1.28 | 1.14 |  |  |  |  |  |  |  |
|  |  | 0.98b | 1.05a | 1.09a | 1.09a |  |  |  |  |  |  |  |

†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.

|  |
| --- |
| 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 2020. 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 | 1812 | 1713 | 1829 | 1669 | 1858 | 1789 | 1738 | 1680 | 0.81 | 0.19 | 0.06 | \*\* | 0.16 | 0.52 | 0.09 |
|  | Sb | 1727 | 1640 | 1918 | 2295 | 1982 | 1997 | 2012 | 1797 |  |  |  |  |  |  |  |
|  |  | 1864b | 2048a | 2059a | 1884b |  |  |  |  |  |  |  |
| Lamberton | Cn | 557 | 533 | 839 | 561 | 568 | 468 | 583 | 527 | 0.11 | 0.11 | 0.46 | \*\*\* | 0.73 | 0.55 | 0.07 |
|  | Sb | 674 | 501 | 814 | 765 | 704 | 635 | 665 | 554 |  |  |  |  |  |  |  |
|  |  | 527b | 726a | 585b | 565b |  |  |  |  |  |  |  |
| Morris | W | 1254 | 1276 | 1133 | 1173 | 1187 | 1187 | 1167 | 1205 | \*\* | 0.27 | 0.42 | \*\*\* | \*\*\* | \* | \*\* |
|  | Sb | 1185 | 1176 | 1447 | 1801 | 1496 | 2176 | 1234 | 1116 |  |  |  |  |  |  |  |
|  |  | 1234b | 1381a | 1497a | 1155b |  |  |  |  |  |  |  |
| Waseca | Cn | 650 | 790 | 680 | 718 | 905 | 703 | 743 | 702 | 0.14 | 0.75 | 0.88 | 0.93 | 0.09 | \* | \* |
|  | Sb | 940 | 710 | 957 | 1011 | 731 | 794 | 904 | 832 |  |  |  |  |  |  |  |
|  |  | 874 | 894 | 872 | 887 |  |  |  |  |  |  |  |

†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.

|  |
| --- |
| Table 8. Summary of main treatment effects for soybean (adjusted to 13% grain moisture) grain yield at four Minnesota locations in 2020. |
|  |  | 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 | 53 | 56 | 53 | 57 | 52 | 55 | 50 | 53 | 0.81 | 0.22 | 0.90 | 0.34 | \*\*\* | 0.68 | 0.89 |
|  | Sb | 51 | 52 | 52 | 55 | 54 | 57 | 55 | 58 |  |  |  |  |  |  |  |
|  |  | 53 | 54 | 54 | 54 |  |  |  |  |  |  |  |
| Lamberton | Cn | 63 | 60 | 64 | 62 | 65 | 63 | 64 | 65 | 0.42 | 0.68 | 0.62 | 0.14 | 0.87 | 0.84 | 0.67 |
|  | Sb | 60 | 61 | 60 | 60 | 63 | 62 | 63 | 63 |  |  |  |  |  |  |  |
|  |  | 61 | 62 | 63 | 64 |  |  |  |  |  |  |  |
| Morris | W | 14 | 18 | 16 | 12 | 19 | 22 | 19 | 20 | 0.65 | 0.75 | 0.07 | \*\* | 0.40 | 0.28 | 0.88 |
|  | Sb | 21 | 18 | 17 | 11 | 20 | 19 | 24 | 21 |  |  |  |  |  |  |  |
|  |  | 18b | 14c | 20ab | 21a |  |  |  |  |  |  |  |
| Waseca | Cn | 78 | 79 | 74 | 77 | 78 | 76 | 78 | 78 | \* | 0.35 | 0.91 | 0.10 | 0.98 | \* | 0.85 |
|  | Sb | 73 | 76 | 71 | 74 | 75 | 73 | 75 | 75 |  |  |  |  |  |  |  |
|  |  | 77a | 74b | 75ab | 76a |  |  |  |  |  |  |  |

†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.

|  |
| --- |
| Table 9. Summary of main treatment effects for corn (adjusted to 15.5% moisture) grain yield at two locations in 2020. |
|  |  | 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 | 212 | 204 | 214 | 210 | 208 | 216 | 212 | 208 | 0.81 | 0.99 | 0.49 | \* | 0.12 | 0.28 | 0.37 |
|  | Sb | 206 | 210 | 206 | 211 | 218 | 221 | 210 | 206 |  |  |  |  |  |  |  |
|  |  | 208b | 210b | 216a | 209b |  |  |  |  |  |  |  |
| Waseca | Cn | 213 | 216 | 214 | 212 | 218 | 191 | 217 | 208 | 0.71 | 0.71 | 0.19 | 0.16 | 0.97 | 0.11 | 0.80 |
|  | Sb | 212 | 224 | 207 | 218 | 207 | 205 | 217 | 213 |  |  |  |  |  |  |  |
|  |  | 216 | 213 | 205 | 214 |  |  |  |  |  |  |  |

†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.

|  |
| --- |
| Table 10. Summary of main treatment effects for hard red spring wheat (adjusted to 13% grain moisture) at two locations in 2020. |
|  |  | 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 | 71 | 70 | 70 | 75 | 73 | 72 | 72 | 75 | 0.52 | 0.88 | 0.35 | 0.19 | \* | \*\* | 0.22 |
|  | Sb | 76 | 72 | 72 | 72 | 74 | 73 | 72 | 73 |  |  |  |  |  |  |  |
|  |  | 72 | 72 | 73 | 73 |  |  |  |  |  |  |  |
| Morris | W | 31 | 37 | 34 | 36 | 30 | 41 | 37 | 35 | 0.73 | 0.73 | 0.39 | 0.29 | 0.42 | 0.45 | 0.26 |
|  | Sb | 36 | 33 | 42 | 39 | 37 | 35 | 35 | 34 |  |  |  |  |  |  |  |
|  |  | 34 | 38 | 36 | 35 |  |  |  |  |  |  |  |

†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.

|  |
| --- |
| Table 11. Summary of main treatment effects for soybean seed mass (on a dry basis) for fertilizer sources and rates at five locations in 2020. |
|  |  | 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 | 127 | 125 | 125 | 128 | 128 | 124 | 126 | 125 | 0.39 | 0.24 | 0.35 | 0.76 | 0.72 | \* | 0.34 |
|  | Sb | 124 | 126 | 124 | 125 | 124 | 124 | 125 | 124 |  |  |  |  |  |  |  |
|  |  | 126 | 126 | 125 | 126 |  |  |  |  |  |  |  |
| Lamberton | Cn | 161 | 155 | 158 | 156 | 161 | 163 | 157 | 161 | 0.44 | 0.73 | 0.53 | \* | 0.22 | 0.08 | 0.63 |
|  | Sb | 160 | 160 | 154 | 156 | 158 | 162 | 160 | 159 |  |  |  |  |  |  |  |
|  |  | 162ab | 160b | 164a | 163a |  |  |  |  |  |  |  |
| Morris | W | 158 | 158 | 150 | 156 | 160 | 163 | 156 | 160 | 0.82 | 0.27 | 0.19 | \*\* | 0.46 | 0.87 | 0.65 |
|  | Sb | 156 | 154 | 155 | 154 | 160 | 156 | 164 | 163 |  |  |  |  |  |  |  |
|  |  | 162a | 158b | 163a | 165a |  |  |  |  |  |  |  |
| Waseca | Cn | 159 | 150 | 157 | 157 | 157 | 159 | 164 | 156 | 0.44 | 0.53 | 0.68 | 0.10 | 0.51 | 0.13 | 0.11 |
|  | Sb | 156 | 154 | 166 | 156 | 154 | 159 | 159 | 159 |  |  |  |  |  |  |  |
|  |  | 158b | 162ab | 160b | 163a |  |  |  |  |  |  |  |

†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.

|  |
| --- |
| Table 12. Summary of main treatment effects for corn seed mass (on a dry basis) for fertilizer sources and rates at three locations in 2020. |
|  |  | 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 | 254 | 258 | 260 | 260 | 255 | 269 | 257 | 260 | 0.45 | 0.07 | 0.27 | \* | 0.30 | 0.75 | 0.58 |
|  | Sb | 247 | 258 | 251 | 251 | 259 | 271 | 252 | 251 |  |  |  |  |  |  |  |
|  |  | 251b | 253b | 261a | 251b |  |  |  |  |  |  |  |
| Waseca | Cn | 277 | 280 | 280 | 272 | 279 | 270 | 275 | 269 | 0.54 | 0.96 | 0.31 | 0.12 | 0.10 | 0.19 | 0.33 |
|  | Sb | 275 | 278 | 279 | 278 | 276 | 270 | 274 | 273 |  |  |  |  |  |  |  |
|  |  | 274 | 272 | 270 | 269 |  |  |  |  |  |  |  |

†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.

|  |
| --- |
| 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 2020. |
|  |  | 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 | 86.9 | 85.6 | 85.0 | 90.0 | 82.6 | 86.0 | 87.2 | 89.2 | 0.98 | 0.60 | 0.94 | 0.30 | \* | 0.39 | 0.15 |
|  | Sb | 87.8 | 90.3 | 84.5 | 84.3 | 89.0 | 85.0 | 87.1 | 87.2 |  |  |  |  |  |  |  |
|  |  | 88.5 | 87.4 | 85.7 | 88.1 |  |  |  |  |  |  |  |
| Morris | W | 106.1 | 106.7 | 106.8 | 106.0 | 108.7 | 81.3 | 109.4 | 78.2 | 0.88 | 0.62 | 0.40 | 0.55 | 0.58 | 0.81 | 0.60 |
|  | Sb | 109.5 | 105.4 | 107.1 | 107.6 | 104.5 | 105.9 | 107.1 | 107.1 |  |  |  |  |  |  |  |
|  |  | 98.8 | 95.6 | 95.7 | 93.1 |  |  |  |  |  |  |  |

†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.

|  |
| --- |
| 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 2020. |
|  |  | 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 | 34.8 | 34.8 | 34.9 | 34.6 | 34.7 | 34.8 | 34.6 | 34.8 | 0.94 | 0.83 | 0.55 | 0.06 | 0.46 | 0.47 | \* |
|  | Sb | 34.8 | 34.8 | 34.7 | 35.0 | 34.5 | 34.5 | 34.7 | 34.2 |  |  |  |  |  |  |  |
|  |  | 35.0a | 35.0a | 34.9ab | 34.7b |  |  |  |  |  |  |  |
| Lamberton | Cn | 33.3 | 33.1 | 33.8 | 33.5 | 33.6 | 33.5 | 33.3 | 33.3 | 0.20 | 0.87 | 0.45 | \* | 0.13 | 0.73 | 0.42 |
|  | Sb | 33.9 | 33.9 | 33.2 | 33.5 | 33.5 | 33.8 | 33.1 | 33.0 |  |  |  |  |  |  |  |
|  |  | 33.9a | 33.7a | 33.7a | 33.3b |  |  |  |  |  |  |  |
| Morris | W | 36.3 | 36.5 | 35.8 | 36.1 | 36.6 | 36.5 | 35.9 | 36.3 | 0.40 | 0.37 | 0.44 | 0.78 | 0.45 | 0.75 | 0.73 |
|  | Sb | 36.0 | 35.8 | 36.3 | 36.0 | 36.1 | 35.8 | 36.0 | 36.5 |  |  |  |  |  |  |  |
|  |  | 36.6 | 36.4 | 36.5 | 36.5 |  |  |  |  |  |  |  |
| Waseca | Cn | 36.8 | 35.9 | 36.1 | 36.5 | 36.5 | 35.8 | 36.3 | 36.0 | \* | 0.55 | 0.22 | \* | \* | \* | 0.24 |
|  | Sb | 36.1 | 36.6 | 35.6 | 36.1 | 35.6 | 35.5 | 36.0 | 36.1 |  |  |  |  |  |  |  |
|  |  | 36.1a | 36.1a | 35.9ab | 35.7b |  |  |  |  |  |  |  |

†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.

|  |
| --- |
| 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 2020. |
|  |  | 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 | 14.9 | 15.3 | 15.6 | 14.9 | 15.4 | 15.3 | 15.4 | 14.9 | 0.80 | 0.16 | 0.68 | 0.11 | \* | 0.89 | \*\* |
|  | Sb | 15.2 | 14.6 | 15.5 | 15.3 | 15.3 | 14.5 | 15.3 | 15.3 |  |  |  |  |  |  |  |
|  |  | 15.1 | 15.4 | 15.2 | 15.4 |  |  |  |  |  |  |  |
| Morris | W | 19.4 | 18.9 | 19.2 | 19.0 | 19.2 | 19.1 | 18.8 | 19.0 | 0.32 | 0.88 | 0.58 | 0.95 | 0.19 | 0.31 | 0.31 |
|  | Sb | 19.0 | 19.1 | 18.8 | 19.0 | 19.0 | 19.1 | 19.1 | 19.0 |  |  |  |  |  |  |  |
|  |  | 18.8 | 18.8 | 18.8 | 18.8 |  |  |  |  |  |  |  |

†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.

|  |
| --- |
| 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 2020. |
|  |  | 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 | 15.3 | 15.0 | 14.9 | 15.2 | 15.2 | 15.0 | 15.4 | 15.1 | 0.35 | 0.66 | 0.35 | 0.26 | 0.61 | 0.38 | \* |
|  | Sb | 14.9 | 15.1 | 15.1 | 15.2 | 15.2 | 15.4 | 15.0 | 15.4 |  |  |  |  |  |  |  |
|  |  | 15.0 | 14.9 | 15.1 | 15.1 |  |  |  |  |  |  |  |
| Lamberton | Cn | 17.1 | 17.4 | 17.2 | 17.3 | 17.3 | 17.3 | 17.2 | 17.3 | 0.13 | 0.12 | 0.66 | 0.33 | 0.25 | 0.77 | 0.63 |
|  | Sb | 17.2 | 17.1 | 17.3 | 17.5 | 17.5 | 17.4 | 17.3 | 17.5 |  |  |  |  |  |  |  |
|  |  | 17.2 | 17.3 | 17.3 | 17.3 |  |  |  |  |  |  |  |
| Morris W/SB | W | 17.5 | 17.7 | 18.0 | 17.8 | 17.6 | 17.5 | 18.0 | 17.5 | 0.89 | 0.28 | 0.40 | 0.75 | 0.43 | 0.56 | 0.51 |
|  | Sb | 17.7 | 18.1 | 17.6 | 17.7 | 17.8 | 17.9 | 17.6 | 17.7 |  |  |  |  |  |  |  |
|  |  | 17.3 | 17.4 | 17.4 | 17.3 |  |  |  |  |  |  |  |
| Waseca | Cn | 15.6 | 15.9 | 15.8 | 15.5 | 15.4 | 15.9 | 15.7 | 15.8 | 0.75 | 0.68 | 0.37 | 0.62 | \* | \* | 0.28 |
|  | Sb | 15.5 | 15.8 | 15.8 | 15.8 | 15.7 | 16.0 | 15.7 | 15.5 |  |  |  |  |  |  |  |
|  |  | 15.7 | 15.7 | 15.8 | 15.7 |  |  |  |  |  |  |  |

†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.

|  |
| --- |
| 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 |

|  |
| --- |
| Table 18. 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 |

|  |
| --- |
| Table 19. 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 |
|  |  | --------------------seed mass (mg seed-1)-------------------- |
| 2020 | Becker | 171a | 160b | 162b |
|  | Morris | 156a | 135b | 139b |
|  | Waseca | 159 | 155 | 158 |
|  |  | ---------------seed protein concentration (%)--------------- |
|  | Becker | 37.4a | 36.7b | 36.9ab |
|  | Morris | 35.1a | 33.9b | 34.6a |
|  | Waseca | 34.4 | 34.3 | 34.6 |
|  |  | ---------------seed oil concentration (%)--------------- |
|  | Becker | 16.8 | 17.0 | 16.9 |
|  | Morris | 17.5b | 17.8a | 17.8a |
|  | Waseca | 17.9 | 17.9 | 17.8 |



Figure 1. Summary of change in soil Cl content at 0-2’ for soybean locations in fall 2020



Figure 2 Summary of change in soil Cl content at 0-2’ for corn and wheat locations in fall 2020



Figure 3. Summary of change in soil K concentration at 0-6” for soybean locations in fall 2020.



Figure 4. Summary of change in soil K concentration at 0-6” for corn and wheat locations in fall 2020.

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

Figure 5. Summary of source and timing main effects on soybean grain yield for each location averaged across the 2018 through 2020 growing season.

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

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 2020 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 2020 growing season. |

**Objective 3 – Amino acid study**

Research into the impacts of soil fertility on protein and oil concentration have been conducted. The impacts on amino acid distribution have not been widely researched. In Minnesota, research on the impact of sulfur on cysteine and methionine content have been studied for soybean and work is currently underway for hard red spring wheat. Some of the research has shown increases in cysteine and methionine in the grain with sulfur but the impacts on other essential and non-essential amino acids have not been fully researched. Since sulfur can change the content of sulfur containing amino acids but may not change the total protein content of the grain, other amino acids must be decreased. One amino acid that has shown to be decreased with sulfur is asparagine. More work should be conducted to better understand the distribution of amino acids to determine if nutrient guidelines should be modified to ensure concentrations of desirable amino acids are maximized in soybean grain.

Evaluate the impacts of macro-nutrients on the distribution of essential amino acids in soybean grain

a) To assess the impact of long-term application of P, K, and S on soybean protein and oil content.

b) To assess the effect of various macronutrients (P, K, and S) on amino acid distribution using NIR.

c) Determine if Cl impacts essential amino acid production.

Methods: For this project we will utilize grain which was collected over six growing seasons from a study funded by AFREC where Two rates (0 and 120 lbs P2O5) of P and two rates of S (0 or 25 lbs S) were applied in a factorial arrangement (-P –S, +P –S, -P +S, and +P +S) ahead of a corn crop in a two-year corn-soybean rotation. Potassium fertilizer was applied over top of the P and S treatments at rates of 0, 100, 200, and 300 lbs K2O per acre. Four sties (Becker, Lamberton, Red Wing, and Rochester) were studied over six growing seasons. Fertilizer was re-applied ahead of each corn crop. The four locations all varied in their response to the three nutrients considering both corn and soybean yield. Soybean protein and oil content was influenced by the fertility treatments. Protein, oil, and selected amino acid concentration were measured by NIR. Since the data reported is from NIR, exact values will not be reported rather trends for increasing (+), decreasing (-), or no (=) impact on protein, oil, or amino acid levels will be reported relative to a non-fertilized control. Changes in the exact values were generally small at plus or minus 0.5 to 1.0% in protein or amino acids which can have a noticeable impact considering total protein or oil produced per acre but a very minor impact in production per bushel. All values were assessed on a dry basis (DB).

**RESULTS**

|  |
| --- |
| Table 20. Protein and oil summary across three soybean crops at four Minnesota locations as impacted by P, S, and K application. |
| Location | P | S | K |
|  | Protein (DB) |
| Becker | = | = | - |
| Lamberton | + | + | - |
| Red Wing | + | + | - |
| Rochester | - | + | - |
|  | Oil (DB) |
| Becker | - | = | = |
| Lamberton | - | - | = |
| Red Wing | = | - | + |
| Rochester | + | - | + |

Table 20 summarizes relative changes in grain protein and oil concentration from the P-K-S trials over three soybean crops at each of the four locations. By the end of the trials in 2017, soybean responded to P at only one location, Becker; soybean response to S occurred at Red Wing and Rochester; and soybean responded to K at Lamberton and Red Wing. All fertilizer was applied ahead of the corn crop in the two-year rotation thus responses were a result of fertilizer carried over from the corn year to the soybean crop.

Soybean protein concentration was increased by P at two and S at three locations. In contrast, P reduced grain protein concentration at one location and K decreased protein concentration at all four locations. The negative impact of K on grain protein concentration has been encountered in previous studies and led to further research on K and Cl impacts on grain protein and oil concentration which will be discussed later. Oil concentrations were typically inversely related to protein where K tended to increase oil concentration while S reduced oil concentration. Less impacts were seen on grain oil concentration compared to grain protein concentration.

|  |
| --- |
| Table 21. Summary of impacts on selected amino acid changes across three soybean crops at four Minnesota locations as impacted by P, S, and K application. |
| Location | P | S | K |
|  | Cysteine (Cys) |
| Becker | = | = | = |
| Lamberton | + | + | = |
| Red Wing | + | + | - |
| Rochester | = | + | = |
|  | Lysine (Lys) |
| Becker | = | = | = |
| Lamberton | + | + | - |
| Red Wing | + | + | - |
| Rochester | - | + | - |
|  | Methionine (Met) |
| Becker | = | = | = |
| Lamberton | + | + | - |
| Red Wing | + | + | - |
| Rochester | + | + | = |
|  | Threonine (Thr) |
| Becker | = | = | = |
| Lamberton | = | = | = |
| Red Wing | - | = | = |
| Rochester | = | + | - |
|  | Tyrosine (Tyr) |
| Becker | = | = | - |
| Lamberton | + | + | - |
| Red Wing | + | + | - |
| Rochester | - | + | - |
|  | Arginine (Arg) |
| Becker | = | = | - |
| Lamberton | + | + | - |
| Red Wing | + | + | - |
| Rochester | - | + | - |
|  | Glutamine (Glu) |
| Becker | = | = | - |
| Lamberton | + | + | - |
| Red Wing | + | + | - |
| Rochester | - | + | = |

The NIR results included several amino acids concentration. However, Table 21 summarizes essential amino acids typically limiting in soybean grain for livestock production (Cys, Lys, Met, Thr, and Tyr) and Arg and Glu which are typically related to high protein production. Two of the amino acids, Cys and Met, are sulfur containing amino acids which were clearly increased through additional sulfur nutrition in the rotation. The exception was at Becker which never responded to S in any of the six years of the study. I have theorized that S in the irrigation water resulted in a limited benefit of S application at Becker for corn or soybean. Sulfur also tended to promote other amino acids such as Lys, Tyr, Arg, and Glu. Since S increased yield at Red Wing and Rochester it could be questioned whether some of the promotion of amino acids could be related to increased yield. Phosphorus also had a positive impact on several amino acids at Lamberton and Red Wing however the impact of P may be a result of S contamination of the fertilizer sources which was assessed at the end of the study. The P rate applied roughly 5 lbs of total S which seemed to impact yield at the Red Wing location and could have additionally impacted protein and amino acid production. While the interactions were not summarized in this report, in many cases there was a P x S interaction where protein or amino acids were enhanced by both nutrients alone but there was no additional impact when P was applied with S compared to S applied alone and P alone did increase protein or amino acids but not to the level of S alone. Potassium more consistently had a negative impact on the essential amino acids, in particular, Lys and Tyr which were consistently lower in the plots with K.

|  |
| --- |
| Table 22. Summary of general changes in grain protein, oil, and amino acid concentrations based on micronutrients boron (B), chlorine (Cl), manganese (Mn), and zinc (Zn). Data are summarized across 12 study locations in Minnesota. |
| Amino Acid | B | Cl | Mn | Zn |
| Protein (DB) | = | + | = | = |
| Oil (DB) | - | + | + | - |
| Cys | - | = | = | + |
| Lys | = | + | + | = |
| Met | = | = | = | = |
| Thr | = | = | = | = |
| Tyr | = | + | = | = |
| Arg | = | + | = | = |
| Glu | = | + | = | = |

A soybean micronutrient response study was conducted in 2013 and 2014 which evaluated soybean response to 2 lbs of boron (B), 20 lbs of chorine (Cl), 10 lbs of manganese (Mn), and 10 lbs of zinc (Zn) across 12 locations ranging from NW to SE Minnesota over the two years of the study. Protein and oil content of the soybean was previously evaluated but data was not summarized for the amino acid results. Table 22 summarizes trends in protein, oil, and amino acid levels based on the additions of each of the micronutrients. Protein was only affected by Cl across the locations. Oil was increased by Cl and Mn while tended to be less when B and Zn were applied. Of the amino acids, Cl had the greatest impact across the amino acids evaluated. Boron, Mn, and Zn only impacted one of the amino acids. It is unclear if the promotion of protein by Cl was the reason for increases in amino acids. The NIR data evaluated amino acid distribution based on the % protein because of specific amino acids. Therefore, the positive impact of Cl should be a result of a greater % of the protein from the specific amino acids. The impact of Cl is interesting. The Cl applied was done so as CaCl2 and Ca was not accounted for in the bulk fertilizer application to each site thus the Ca applied also could be impacting protein and amino acid distribution.

|  |
| --- |
| Table 23. Summary of general changes in grain protein, oil, and amino acid concentrations based on IDC severity and the use of an in-furrow iron chelate at various levels of IDC severity. |
|  | IDC Severity | With Fe Chelate (by IDC Severity) |
| Amino Acid | Low | Moderate | High |
| Protein (DB) | = | = | = | = |
| Oil (DB) | = | = | = | = |
| Cys | = | = | = | = |
| Lys | = | = | = | = |
| Met | = | = | = | = |
| Thr | = | = | = | = |
| Tyr | = | = | = | = |
| Arg | = | = | = | = |
| Glu | = | = | = | = |

Table 23 summarizes data collected by a iron chlorosis trial funded by Minnesota Soybean from 2015 through 2017. Follow up analysis was completed looking at amino acid concentrations where there was no impact of IDC severity on the distribution of amino acids listed in Table 20. In addition, there was no effect of iron chelate use on amino acid distribution. The dataset also included soybean varieties that varied in IDC tolerance. Differences in amino acids did exist between varieties which was expected. The data is not included in this report.

|  |
| --- |
| Table 24. Relative impacts of sources of K, Cl and S on soybean grain protein, oil, and amino acid changes across four locations and in Minnesota and two rates of application during the 2018-2021 cropping season. |
| Amino Acid | +K | +Cl | +S |
| Protein (DB) | - | + | - |
| Oil (DB) | + | = | = |
| Palmitic acid | = | + | = |
| Stearic acid | = | = | = |
| Oleic acid | - | = | = |
| Linoleic acid | + | = | = |
| Linolenic acid | = | = | = |
| Ala | - | + | - |
| Arg | - | = | = |
| Asp | - | + | - |
| Cys | - | + | - |
| Gln | - | + | - |
| Gly | - | + | - |
| His | - | = | - |
| Ile | - | = | - |
| Leu | - | + | - |
| Lys | - | + | - |
| Met | - | = | = |
| Phe | - | = | = |
| Pro | - | + | = |
| Taurine | - | + | - |
| Thr | = | = | = |
| Trp | - | + | - |
| Tyr | - | - | = |
| Val | - | = | = |

Soybean data from the primary field trial outlined in the first part of this report was further evaluated to study Cl impacts on amino acids and protein and oil. The micronutrient study from Table 22 indicated some increase in soybean protein concentration when Cl was applied as CaCl2. However, data from the K source trial indicated no impact of CaCl2 on protein and oil or amino acid levels. It should be noted that the data from Table 22 includes 12 locations while Table 24 includes 4 locations with data averaged over four years (2018-2021). Data was collected from soybean trials from the K source study in 2017 but was not included in Table 24 as only half of the treatments were applied during the first year of the study. The data in Table 24 are broken down based on response to individual nutrients, K, Cl, and S. Protein was negatively impacted by K and was positively affected by Cl which could be due to a general reduction in soybean grain yield from Cl. Protein concentration was not impacted by S. Seed oil concentration was increased by K and was not impacted by Cl or S. Potassium negatively impacted nearly all measured amino acid concentration distributions with the exception of threonine which was not impacted by K. Oleic acid distribution was also reduced by K, while linoleic acid was slightly greater with K. Chloride application increased roughly half the amino acids measured. Sulfur decreased several amino acids and did not result in an increase in any, particularly the two-sulfur containing amino acids, cysteine and methionine. The general decrease due to S could be a result of the only S containing treatment also contained K and the K effect may have been greater than the S effect. Other research has shown that S tends to increase the relative amount of cysteine and methionine so the decreases in this case may not reflect the true impact of S. There was no increase in amino acid concentration with is puzzling since data showed a general decrease in most, particularly when K was applied. The majority of the other amino acids measured did not show a clear increase following K application thus there likely is an unmeasured fraction that may have been impacted positively by K to account for decreases in some sources. Since the measured values are given as a distribution then if one amino acid decreases another must increase.

An AFREC funded project was established in 2019 to determine rate and timing effect of P fertilization on soybean yield. Grain samples were saved for further amino acid analysis and the data from 2019-2021 are summarized in Table 25. Only the effect of P rate is summarized in Table 25. Timing data were not summarized for this report. Grain protein and oil concentration were not affected by P. All amino acids were generally increased when P was applied with none being decreased. Similar to the previous data summarized in Table 24 I would have expected a specific faction to decrease with the general increase in amino acids. It also should be noted that the application of P generally increased the yield of soybean as the sites selected tested low in P. Therefore, any increase in an amino acid fraction may be more a result of lack of P resulting in poor yield lowering grain quality in soybean. Additional P data were listed in Table 21 but for sites again that yield responded to P. What I can conclude is that addressing soils deficient in P is important also to ensure optimal grain quality as well as optimal yield. I do not know if application of P in excess of crop needs would result in increases in essential amino acids.

Table 25. Relative impact of P on soybean grain protein, oil, and amino acid changes across six locations and in Minnesota from 2019-2021.

|  |  |
| --- | --- |
|  | +P |
| Protein (DB) | = |
| Oil (DB) | = |
| Palmitic acid | = |
| Stearic acid | = |
| Oleic acid | + |
| Linoleic acid | = |
| Linolenic acid | - |
| Amino Acid |
| Ala | + |
| Arg | + |
| Asp | + |
| Cys | + |
| Gln | + |
| Gly | + |
| His | + |
| Ile | + |
| Leu | + |
| Lys | + |
| Met | + |
| Phe | + |
| Pro | + |
| Taurine | + |
| Thr | = |
| Trp | + |
| Tyr | = |
| Val | = |

**Conclusions**

 The data for the amino acid works shows that there is a linkage between nutrient management and the distribution of amino acids in soybean grain. It has to be noted that we were only looking at trends in the data and were not focused on exact values of amino acids as NIR is not the best way to analyze for the exact amino acid content of the grain but will give an idea of how the profile may change based on fertilizer nutrient application.

Optimal management of phosphorus tended to promote higher seed quality, especially increasing the relative proportion of essential amino acids. Potassium on the other hand has consistently shown to negatively impact grain quality, especially protein concentration and the distributions of several amino acids. The protein concentration decrease is consistent across all studies. Past long terms studies have shown that grain protein concentration is reduced in soybean by K regardless of when it is applied in the rotation. Therefore, applying only the amount of K needed for the crop would be a suggested practice to try to maintain high quality soybean grain. I had theorized that the Cl in KCl fertilizer could have played a part in the negative impact of K on grain quality but from the data in the current studies Cl tended to decrease yield which resulted in positive benefits on soybean grain quality. I do not suggest high rate of Cl be applied as the resulting yield loss will likely not offset any benefits of the Cl on increasing protein concentration as well as higher concentrations of beneficial amino acids.

Using K sulfate instead of KCl did not appear to be beneficial but I have current research studies focused on blending K sulfate with KCl. While the amino acid work has ended for my current soybean projects, I will continue to look at amino acid distribution with K sulfate. Based on this information the primary suggestion I would have for soybean growers is to not over apply K. Even though the soybean plant removes more K in the harvested grain there is no evidence that K should be always applied ahead of soybean to increase grain yield. There has been only one instance where application of K every year resulted in greater soybean yield, which was data collected from my 10-year long-term study at Morris funded by the Minnesota Soybean Growers.

I still would like to know what fraction of the amino acid profile is changing in response to the changes identified in the tables above as the NIR data was not clear as to a resting decrease in one amino acid fraction with the increase in another. One past change of not was sulfur increasing cysteine and methionine in wheat grain while reducing asparagine (which was not reported with the NIR data). Micronutrients and treatments to correct IDC did not impact soybean seed quality.