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Meta-analysis of Winter Wheat Response to Chloride Fertilization in Kansas

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Cereal grain yield response to chloride (Cl) fertilization has been reported in most of the Great Plains. The objective of this study was to use meta-analytic methods to summarize and provide quantitative estimates of the effects of soil and fertilizer Cl on wheat (Triticum aestivum *L.*) *response including grain yield and flag leaf Cl tissue level. Meta-analysis evaluated the effect of soil and fertilizer Cl application from different studies on a common scale of effect size. Chloride tissue concentration using the flag leaf correlated well with fertilizer plus soil Cl at a depth of 0–60 cm. However, our analysis indicates possible luxury uptake of Cl in relation to grain yield, with a possible upper limit in plant uptake with soil Cl levels around 68 kg Cl ha^{-1}. Application of Cl fertilizer generated average wheat yield increases of approximately 8%.*

Keywords Chlorine, fertilizers, wheat

Introduction

Chlorine (Cl) occurs in soil solution as the anion chloride (Cl^-), which is readily absorbed by crops. Because Cl is usually supplied to crops as chloride from various sources, including soil reserves, irrigation water, fertilizers, and atmospheric deposition, chloride deficiency is uncommon in many regions. Soils of the Great Plains region of the United States typically show high levels of extractable potassium (Fixen et al. 2010); however, documented responses to potassium chloride (KCl) application in the region have been linked to Cl response (Christensen et al. 1981; Fixen et al. 1986a; Miller 1998; Skogley and Haby 1981). Most of the Cl in soils is present in the soil solution as Cl^- ions, which arrives from rainfall, marine aerosols, volcanic emissions, irrigation water, and fertilizers (Havlin et al. 1999). Deposition values from precipitation are considered to be significantly greater in coastal areas. Recent reports on atmospheric deposition show much lower values across much of the Great Plains, ranging from 0.2 to 0.5 kg ha^{-1}, compared to typical deposition levels of 10 to 30 kg Cl^- ha^{-1} in coastal regions (NADP 2011). Substantial amounts of Cl also can be found in irrigation water; this is often enough to meet crop needs (Mikkensen 2005). In areas that have low levels of potassium (K), Cl is typically added as KCl fertilizer, thus increasing Cl concentration in the soil and likely covering Cl needs (Engel et al. 1997). However, plant Cl uptake and the concentration of Cl in plant tissue seems to correlate primarily with soil Cl levels. Traditionally, soil Cl has been evaluated primarily

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for potential issues with salinity and plant toxicity, but Cl can limit crop yields in soil and environmental conditions like those in the Great Plains. Research on Cl fertilization for crop production has been limited in this region; outside the Great Plains, Cl nutrition for crop production has been considered sufficient so no responses to Cl fertilization have been documented.

Chloride plays important roles in enzyme activation (Broyer et al. 1954) and osmotic regulation (Christensen et al. 1981; Kafkafi and Xu 2002). Perhaps one of the most important roles of Cl in plant growth is in the suppression of plant disease. Suppression of disease through Cl fertilization also has been reported in other crops, including corn and barley (Heckman 2007). Poor Cl nutrition in wheat has been associated with greater incidence of diseases such as take-all root rot caused by *Gaeumannomyces graminis* var. tritici (Christensen et al. 1981) and common root rot caused by *Fusurium culmorum* (Engel and Grey 1991; Shefelbine, Mathre, and Carlson 1986). This suggests that Cl fertilizer response also would be affected significantly by environmental factors associated with disease pressure, particularly in regions with naturally low levels of soil Cl, and that year-to-year variability may be significant. In addition, cultivar selection would determine potential response to Cl fertilization, which is connected to the performance of each cultivar under disease pressure.

Chloride, like nitrate [NO_3 nitrogen (N)], is mobile in the soil, and as result a profile (0–60 cm deep) soil test is recommended in many regions to determine the amount of available Cl in the soil (Fixen et al. 1987). Under conditions of high rainfall Cl is prone to movement in the soil profile through leaching. However, under conditions of low precipitation such as the Great Plains, Cl has been suggested to stay in the soil and to correlate to wheat yield response (Fixen et al. 1986b). In many regions of the Great Plains a profile (0–60 cm deep) soil sampling is recommended for Cl and N status. Critical whole-plant tissue concentration has been suggested for Cl in winter wheat (Engel, Bruckner, and Eckhoff 1998). Under arid conditions with minimum leaching, Cl would likely remain in the soil profile, and upward Cl movement could be expected because of evapotranspiration. Given these conditions Cl response may be more frequent in the eastern plains, where precipitation is usually higher than in western regions.

Chloride accumulation in plant biomass is usually greatest at maximum plant growth; however, Cl can leach from the biomass after senescence. Chloride removal with grain harvest is usually considered minimal, but if biomass is harvested Cl removal can be significant. Chloride plant uptake typically is correlated with fertilizer and soil Cl levels, but correlation with relative grain yield can fall into a broad critical range and is therefore imprecise. The main objective of this study was to summarize and provide quantitative estimates of the effect of soil and fertilizer Cl on wheat response using meta-analytic methods.

Materials and Methods

Database Compilation

Published articles from the Kansas Fertilizer Research Report of Progress (Agronomy Research, Kansas State University Agricultural Experiment Station and Cooperative Extension Service 2010) were used to construct a database including published studies from 1990 to 2006. Each study quantified the response of winter wheat to chloride fertilization, including grain yield and Cl tissue analysis. All locations were farmed under dryland conditions in areas with typically high native soil K levels and no history of KCl fertilizer application. Studies included in this analysis were conducted at 53 locations in

Kansas and primarily evaluated chloride application rate and chloride source (Table 1). Ideally each study provided soil Cl level at a depth of 0–60 cm, grain yield, and Cl tissue collected at the boot stage (Feekes 9 growth stage; Large 1954). Chloride fertilizer application was completed as a top-dress application before the Feekes 6 growth stage (Large 1954) for all studies included in this analysis. Soil Cl analyses in all studies were completed using a calcium nitrate extraction, and Cl leaf tissue analyses were completed using the calcium sulfate extraction method. Aliquots were analyzed colorimetrically by the mercury(II) thiocyanate method (Gelderman, Denning, and Goos 1998).

All articles used standard methods for experimental design, with approximately 80% using randomized complete block design and about 20% using complete randomized designs with three to six replications. We assumed homogeneous designs and methods and generation of similar sampling errors across studies (Gurevitch and Hedges 2001).

Statistical Analysis

In using a meta-analysis approach, we aimed to evaluate the effect of soil and fertilizer Cl from different studies on a common scale of effect size. The response ratio was estimated based on the ratio between wheat response (yield or Cl tissue concentration) from plots with Cl fertilizer to wheat response from plots without Cl and was used to evaluate the effect of Cl fertilizer application on wheat (Hedges, Gurevitch, and Curtis 1999). Data are presented as relative responses [(treatment-control) / control) $\times$ 100]. SAS software was used for analysis (SAS Institute 2010) following methods described by Wang and Bushman (1999).

In addition to the response ratio, a nonlinear function was used to describe wheat response to soil and fertilizer Cl. For this analysis the clustering structure of the data was organized with "study" as the first level and "location" at the second level. This structure was modeled as random effects to allow the evaluation of soil and fertilizer Cl effects on wheat response across studies and locations (St-Pierre 2001). A nonlinear mixed effect model was fitted (Pinheiro et al.) using the PROC NLMIXED procedure with a nested nonlinear random effect model with two levels of the experimental unit (study and location) and using the proper variance–covariance matrix (Littell et al. 2006; SAS Institute 2010). Relative grain yield and Cl tissue was described by the exponential Mitscherlich function as modified by Klausner and Guest (1981): $y = A - B \exp - Cx$, where y is wheat response, A is maximum wheat response, B is the response difference between A and the unfertilized control treatment, C is a constant, and x is the level of soil and fertilizer Cl. The random effects (locations nested within study) and the error were assumed to follow a normal distribution. Adjusted response values (adjusted y) were calculated by adding the residuals to their corresponding "y predicted" values (St-Pierre 2001). Relative yield and Cl leaf tissue were calculated for each location within a study by expressing the mean value of all treatment means as percentages of the mean for the greatest value in that location. Segmented polynomial (quadratic plateau) response models were fitted to the relationship between flag leaf Cl tissue concentration and relative wheat grain yield using the PROC NLMIXED procedure in SAS 9.2 (SAS Institute 2010). This model also used "study" and "location" within study effects as random.

Results and Discussion

Relative grain yield response with the application of Cl fertilizer increased as much as 20% over the control (Figure 1). Separation by Cl fertilizer application rate category shows no difference in yield response, including application rates as high as 90 kg Cl ha^{-1} (Table 1

Table 1
Studies included in the database for the analysis of winter wheat response to Cl fertilizer application

Study	Year	County	Cl application rate (kg ha^{-1})	Soil test Cl (kg ha^{-1})
1	1990	Finney	0, 11, 22, 45, 90	10.5
		Marion A	0, 11, 22, 45, 90	2.5
		Marion B	0, 11, 22, 45, 90	4.8
		Wabaunsee	0, 11, 22, 45, 90	2.5
2	1991	Marion	0, 17, 34, 67	24.6
		Shawnee	0, 11, 22, 45, 90	40.3
		Stevens	0, 11, 22, 45, 90	17.9
3	1992	Marion A	0, 17, 34, 50	17.9
		Marion B	0, 17, 34, 50	23.5
		Marion C	0, 17, 34, 50	28.0
4	1992	Marion A	0, 17, 34, 50	16.8
		Marion B	0, 17, 34, 50	7.8
		Osage	0, 17, 34, 50	9.0
5	1994	Cowley	0, 11, 22, 34	15.7
		Marion E	0, 11, 22, 34	17.9
		Marion W	0, 11, 22, 34	24.6
6	1995	Cloud	0, 11, 22, 34	16.1
		Marion A	0, 11, 22, 34	18.1
		Marion B	0, 11, 22, 34	24.2
7	1996	McPherson	0, 11, 22, 34	42.1
		Saline A	0, 11, 22, 34	16.1
		Saline B	0, 11, 22, 34	36.3
8	1996	Cowley	0, 11, 22, 34	10.1
		Marion A	0, 11, 22, 34	15.7
		Marion B	0, 11, 22, 34	10.1
9	1997	Marion	0, 22, 45	7.8
		Saline	0, 22, 45	15.7
10	1997	Marion A	0, 11, 22	39.2
		Marion B	0, 11, 22	48.2
11	1997	Marion	0, 22, 45	7.8
		Saline	0, 22, 45	24.6
12	1998	Ellsworth	0, 22	7.8
		Kingman A	0, 22	4.5
		Kingman B	0, 22	4.5
13	1998	Marion A	0, 11, 22	34.7
		Marion B	0, 11, 22	17.9
		Marion C	0, 11, 22	15.7

(*Continued*)

Table 1
(Continued)

Study	Year	County	Cl application rate (kg ha^{-1})	Soil test Cl (kg ha^{-1})
14	1999	Saline	0, 22	7.8
		Stafford	0, 22	7.8
15	1999	Marion A	0, 11, 22	20.2
		Marion B	0, 11, 22	11.2
16	2000	Saline	0, 11, 22	15.7
		Stafford	0, 11, 22	16.8
17	2002	Marion A	0, 11, 22	10.1
		Marion B	0, 11, 22	50.4
		Stafford	0, 11, 22	10.1
18	2002	Marion	0, 11, 22, 34	24.2
		Republic	0, 11, 22, 34	16.8
19	2005	Harvey	0, 11, 22, 34	19.4
		Republic	0, 11, 22, 34	15.7
20	2006	Finney	0, 11, 22, 34, 45	17.9
		Greeley	0, 11, 22, 34	20.2

and Figure 1). This suggests that grain yield response is better with the initial 0–21 kg Cl ha^{-1} application and that grain yield does not continue to increase with application rates in Kansas. Initial Cl soil levels also determine the potential response to additional Cl fertilizer application. Average yield increase across locations and studies was approximately 8%. These results and relative yield increases are similar to previous studies conducted in other locations (Diaz-Zorita, Duarte, and Barraco 2004; Freeman et al. 2006; Koenig and Pan 1996). Yield response seems to vary widely and likely is affected by levels of soil Cl and the use of responsive varieties. Variety selection can significantly affect yield response to Cl fertilization (Lamond, Roberson, and Rector 1999). Chloride is considered to improve overall plant health, and response to Cl fertilizer application can be directly related to variety resistance to diseases and natural pressure of the disease in a given growing season (Christensen et al. 1981; Engel and Grey 1991; Miller 1998). Therefore, the likelihood of yield responses may depend not only on soil and fertilizer Cl but also on seasonal factors and variety performance in the presence of diseases.

Chloride tissue collected at the boot stage (Feekes 9 growth stage) follows a trend similar to yield (Figure 2), but the relative increases in Cl tissue concentrations are significantly greater with an average increase of 114%. When data are separated by fertilizer application categories and across all soil Cl levels, differences in relative Cl tissue response are similar.

An exponential relationship developed between relative grain yield of wheat and soil Cl (0–60 cm deep) plus Cl fertilizer applied (Figure 3). A soil plus fertilizer Cl level of approximately 61 kg Cl ha^{-1} was needed to achieve a 95% yield potential across studies and locations. This value is in agreement with current recommendations for optimum soil Cl

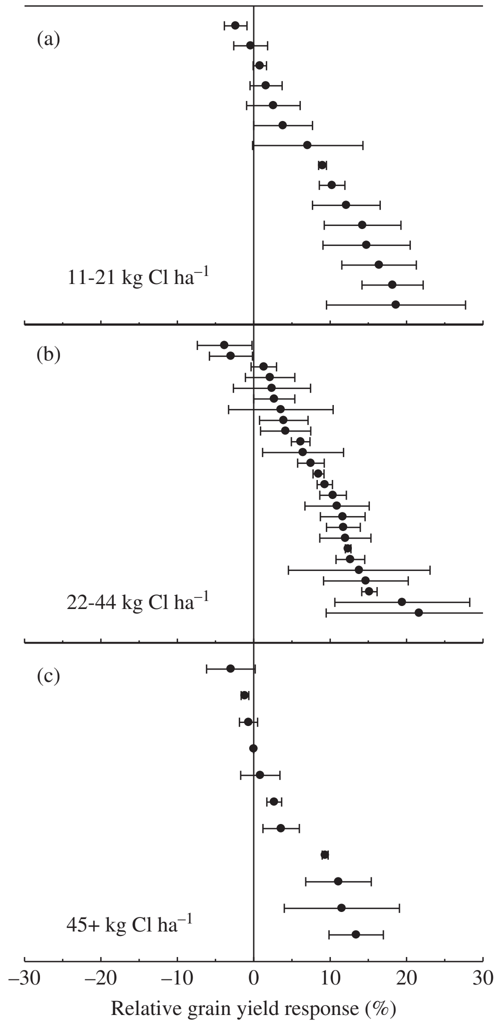

Figure 1. Relative response [(treated-control) / control × 100] of winter wheat grain yield to Cl fertilizer by application rate category (a) 11–21 kg ha^{-1}, (b) 22–44 kg ha^{-1}, and (c) more than 44 kg ha^{-1}. The horizontal bars represent standard error of the mean.

levels in Kansas (Leikam, Lamond, and Mengel 2003), and slightly greater than previously suggested critical levels of 44 to 53 kg Cl ha^{-1} by others (Diaz-Zorita, Duarte, and Barraco 2004; Fixen et al. 1987; Fixen et al. 1986b; LaRuffa et al. 1999).

Relative Cl concentration in the leaf tissue at boot stage (Feekes 9 growth stage) increased as soil plus fertilizer Cl increased (Figure 4). The exponential relationship suggests a soil plus fertilizer Cl level of approximately 68 kg Cl ha^{-1} to achieve 95% of maximum flag leaf Cl accumulation. This value is greater than the calculated value with grain yield parameter. A previous study by Fixen et al. (1986b) showed good correlation of whole plant Cl concentration with soil Cl levels at 0–60 cm deep with a linear relationship of soil Cl and whole plant Cl concentration. That study also evaluated soil Cl levels at 0–120 cm deep and showed a weak relationship with plant response compared to the 0-

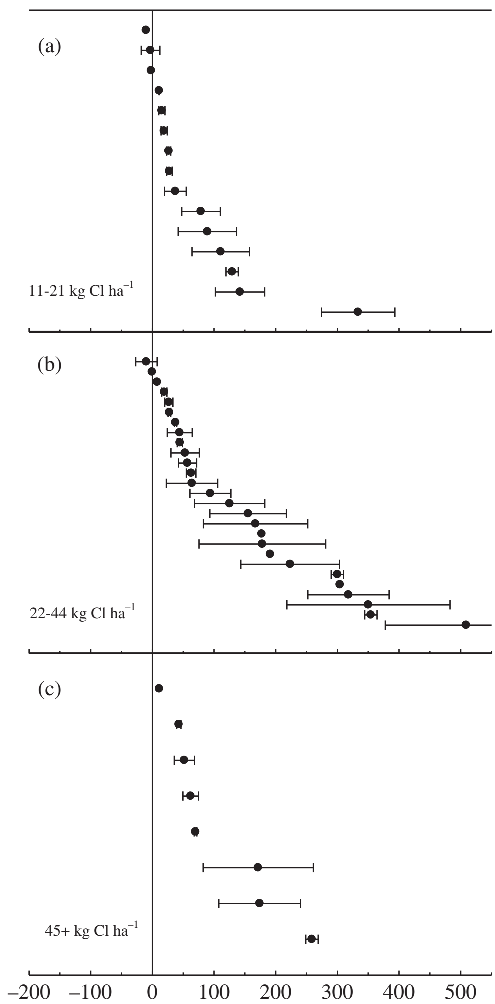

Figure 2. Relative response [(treated-control) / control × 100] of Cl tissue content at booth stage in winter wheat as affected by Cl fertilizer. Application rate categories are (a) 11–21 kg ha^{-1}, (b) 22–44 kg ha^{-1}, and (c) more than 44 kg ha^{-1}. The horizontal bars represent standard error of the mean.

to 60-cm sampling depth. Because grain yield increases are small (Figure 3) compared to relative flag leaf tissue Cl concentration, the observed increases in response to soil and fertilizer Cl must be attributed mostly to uptake of Cl beyond needs for grain production. This is supported by Figure 5, which shows a weak relationship between relative wheat grain yield (RGY) response and Cl increase in flag leaf tissue. Studies using whole-plant tissue Cl concentration as a predictor of potential yield response to Cl fertilization suggested little value of tissue Cl in some regions (Engel and Grey 1991), whereas other studies suggest that whole-plant Cl tissue concentration is a good diagnostic tool for assessment of relative grain yield response (Engel, Bruebaker, and Emborg 2001; Fixen et al. 1987).

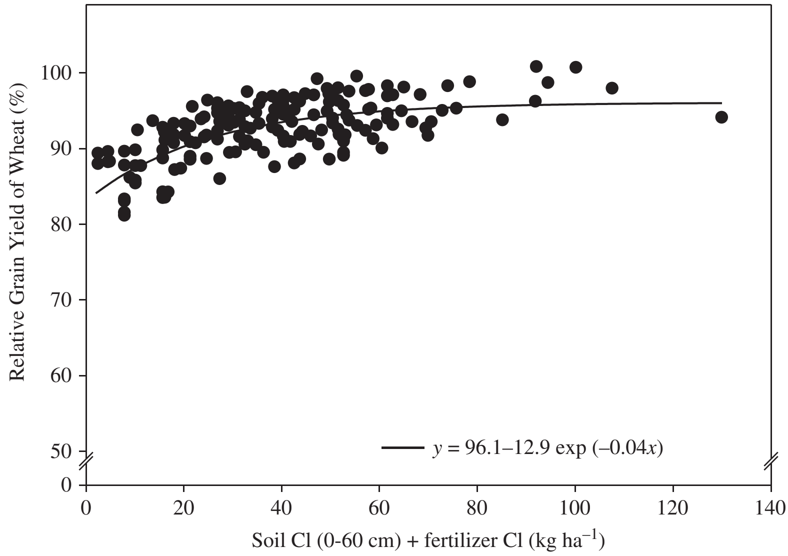

Figure 3. Relative winter wheat yield as a function of soil Cl (0–60 cm deep) plus Cl fertilizer across all studies and locations. Values are adjusted observations and the mean regression line across studies and locations from the nonlinear mixed model analysis.

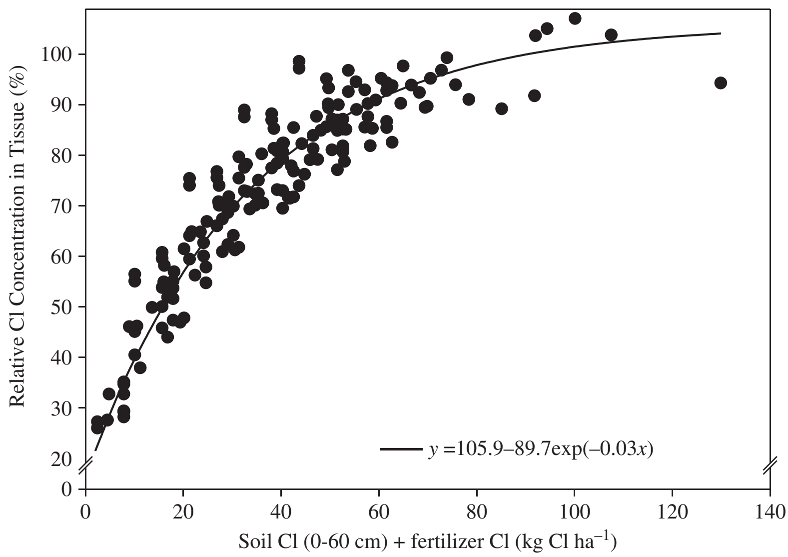

Figure 4. Relative winter wheat tissue concentration as a function of soil Cl (0–60 cm deep) plus fertilizer Cl across all studies and locations. Values are adjusted observations and the mean regression line across studies and locations from the nonlinear mixed model analysis.

Engel, Bruckner, and Eckhoff (1998) developed critical whole-plant Cl tissue concentration levels for winter wheat and spring wheat, but they suggested that small yield responses were observed even under low Cl status as determined by tissue concentration. Nutrient concentration can vary significantly in different parts of the same plant, and a whole-plant

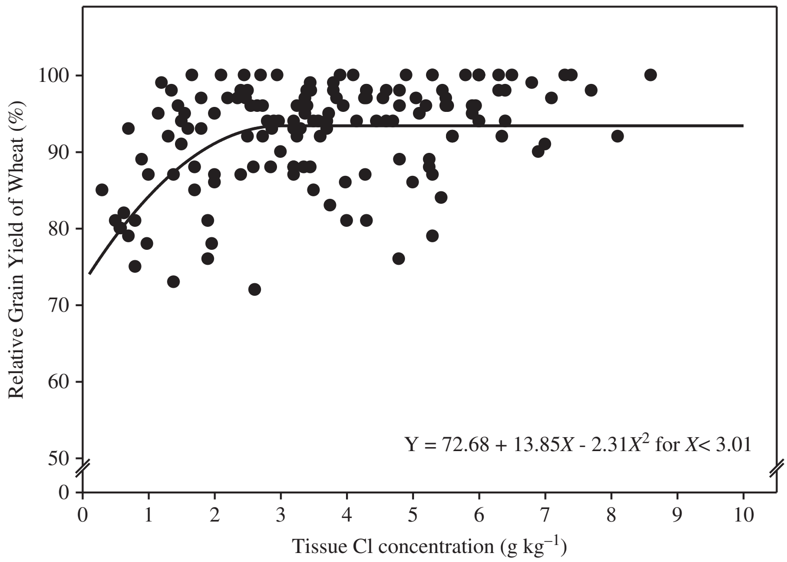

Figure 5. Relationship between relative winter wheat grain yield and the Cl concentration of tissue across soil Cl level and Cl fertilizer rates.

Cl tissue concentration likely includes plant parts that are better indicators of potential grain yield response than others. Studies included in our analysis used the flag leaf as an indicator of plant Cl status instead of whole-plant tissue. This suggests that assessment of Cl supply for wheat using plant parts may require additional evaluation to test how other sampling timing and plant parts may predict the optimum concentration range for grain yield. Little attention has been given to the evaluation of various plant parts for Cl nutrient status, particularly for supply levels that fall into the optimum to excessive range for grain yield. Tissue tests may be particularly useful in regions where yield response to Cl fertilizer application is unlikely. A good soil tissue test that can distinguish not only deficiency but also excess is particularly important for a nutrient such as Cl that is associated with potential yield reductions at excess levels.

Conclusions

Wheat production in the Great Plains can be improved with the application of Cl fertilizer, which generates average yield increases of approximately 8%. Separation by the Cl fertilizer application rate category shows no difference in yield response, including application rates of up to 90 kg Cl ha^{-1}. Our results indicate that Cl fertilizer application at rates greater than 21 kg Cl ha^{-1} would seldom result in additional wheat yield increase in the Great Plains region of Kansas.

Chloride tissue concentration using the flag leaf correlated well with fertilizer plus soil Cl at 0–60 cm deep. However, our analysis indicates possible luxury uptake of Cl in relation to grain yield, with a possible upper limit in plant uptake with soil Cl levels around 68 kg Cl ha^{-1}. Using flag leaf tissue, Cl concentration shows value as a potential indicator of grain yield response; however, additional research is necessary to evaluate optimum sampling timing and plant parts for Cl in wheat.

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