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Response of Winter Wheat to Chloride Fertilization in Sandy Loam Soils

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Abstract: Chloride (Cl) as a yield and growth-limiting nutrient has been the object of experimental attention for the last several decades. Long-term experiments were conducted from 1996 to 2002 at Hennessey and Perkins, Oklahoma to evaluate the response of winter wheat grain yield and nitrogen (N) uptake to 0, 15 and 30 kg Cl ha^{-1} rates. A randomized complete block experimental design with three replications was used at both sites. Grain yield data were subjected to statistical analysis using SAS. Polynomial Orthogonal contrasts were used to detect trends in grain yield and N uptake to chloride levels. Chloride fertilizer significantly increased wheat grain yields in 50% of the site-year combinations (14 total site years), and the increases were more notable on the sandy loam soil included in this study.

Keywords: Calcium chloride, chloride, grain yield, winter wheat

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INTRODUCTION

Chloride (Cl) is an essential plant nutrient involved in several processes taking place in the plant including osmotic regulation (Kafkafi and Xu 2002); photosynthesis by evolution of oxygen (O_2) in photosystem, enzyme activation, and transportation of other plant nutrients (Broyer et al. 1954; Ozanne, Woolley, and Broyer 1957; Grant, Lamond, and Mohr 2003); plant development; lodging prevention, and disease suppression (Wallace 1944; Engel, Bruebaker, and Emborg 1994). Chloride has also been found to control physiological leaf spotting in some winter and durum wheat varieties and barley (Smiley, uddin, et al., 1993; Engel, Bruebaker, and Emborg 2001).

As a yield-and growth-limiting nutrient, Cl has been the object of experimental attention for the past several decades. However, recent publications related to Cl nutrition contained contradicting reports, where some reported the importance of supplementing crops with this nutrient but others not. The latter conclusion arises from the fact that Cl is required by plants in a very small amount, and this amount can be obtained from the processes in the soil and the surrounding environments plus from fertilizers designed to supply crops with macronutrients such as potassium (K) and calcium (Ca) (e.g., KCl and $CaCl_2$) (Carr, Martin, and Melchior 2001). These compounds contain some chloride that can be used by crops to satisfy their requirement. Annual chloride depositions of 13 to 40 kg ha^{-1} in precipitation are common and may increase to more than 112 kg ha^{-1} in coastal areas (Lamond and Leikam 2002). Because of the distance away from seawater high in Cl, inland areas are known to receive much lower amounts of Cl in rainfall. Several of the current Cl-related research activities are focused on the benefits obtained from Cl in suppressing foliar and root diseases (Miller 1998; Miller and Jungman 1998; Engel and Grey 1991; Christensen and Brett 1985; Thomason et al. 2001) rather than on grain yield.

However, there are several research studies that demonstrate the importance of fertilizing crops with Cl in the United States and elsewhere to maintain grain yields, especially in soils where the soil Cl is low, such as sandy and sandy loam soils (Sillanpää 1982). According to Glant, McLaren, and Johnston (2001), soil Cl levels less than 36 kg ha^{-1} in the top 0.6 m of soil are generally used as an indication of insufficient quantity, and a level of 36–72 kg ha^{-1} is assumed to be adequate. Chloride response to yield follows the concept of response of crops to mobile nutrients. This means the yield can be related directly to the amount of Cl, given that this nutrient is the most limiting one in the soil. It is also important to note that Cl is mobile and subject to leaching. Research conducted on coarse-textured Mollisols in Argentina showed that Cl fertilization increased wheat grain yields in 50% of the sites. Averaged over 10 locations, the grain yield benefit due to chloride fertilization was 253 kg ha $^{-1}$ and it was mostly explained by a greater number of grains per square meter (Díaz-Zorita, Duarte, and Baracco 2004). Soil Cl levels of 13.2 mg kg^{-1} were adequate for maximum grain yields (Díaz-Zorita, Duarte, and Barraco 2004). Research conducted in Canada between 1996 and 1998 on clay loam and fine sandy loam textured soils revealed that soil Cl levels were low in all years at the fine sandy loam site and in 1996 and 1998 at the clay loam site (Roberts 1999). Research in the Great Plains showed that Cl significantly increased wheat grain yields by as much as 1546 kg ha^{-1} at three sites, increasing gross return by \$50 ha^{-1} (Lamond, Roberson, and Rector 1999). Generally, wheat grown in Cl-deficient soils responded positively to Cl rates less than 50 kg ha^{-1}. Research findings suggest that soil (0–25 cm) Cl levels less than 33 kg ha^{-1}, will require 22 kg Cl ha^{-1} applied as KCl (Lamond and Leikam 2002). Further, the concentration of Cl in wheat should be 0.4% in the whole plant at the boot to flowering stage to achieve maximum yield potential (Lamond 2003). Research conducted in the Great Plains of the United States showed that yield response occurs about half the time when plant Cl is between 0.12 and 0.4%, but it occurs 80% of the time when plant Cl concentrations are 0.12% or less (Lamond 2003). Similar results were also reported from research conducted in the Pacific Northwest regions of the United States, where Cl fertilization practices increased productivity of wheat and other crops (Grant, Lamond, and Mohr 2003; Engel et al. 1997).

One of the important functions of Cl as a whole is its significance in suppressing some foliar diseases. In this respect, several research findings were published (Miller and Jungman 1998; Engel and Grey 1991; Christensen et al. 1981) that documented the benefits of Cl fertilization in lowering the negative effects of disease during the development of the crops and the subsequent improvement in yield. In Texas, topdress applications of Cl have caused significant reduction of leaf rust and septoria ratings at bloom and significant yield responses. They found a strong positive and significant interaction between Cl and systemic foliar fungicides, which are commonly used in wheat (Miller and Jungman 1998).

Some researchers attribute the Cl effect to nondisease wheat growth-limiting factors (Engel, Ecknoff, and Berg 1994; Fixen 1993). According to these researchers, Cl fertilization is beneficial in preventing the occurrence of a leaf spot syndrome that is not disease related (Engel et al. 1997; Smiley, Gillespie-Sasse, et al., 1993). In support to their argument, they suggested that 48 kg ha^{-1} Cl fertilization decreased physiological leafspot on winter wheat in Saskatchewan.

Others claim that Cl may increase wheat grain yields by enhancing NH_4^+ supply attributed to lower leaf osmotic potentials, delayed nitrification in the soil, and inhibition of take-all root rot (*Gaeumannomyces graminis*) disease (Christensen and Brett 1985; Koening and Pan 1996). This is an interesting aspect of Cl because this indicates that the uptake of major nutrients such as N depends on its availability in the soil. In fact, several researchers underlined Cl's role in uptake of other nutrients, especially macronutrients such as N.

In Oklahoma, research conducted for 8 years on the effect of Cl on wheat grain yield and take-all disease found that only in 2 years' yield was significantly affected by Cl levels (Thomason et al. 2001). This was apparently because of the high Cl level in the soil of the experimental site, which was a silty loam. Soil survey research across the state, however, revealed that about 32% of soil samples collected from 17 counties had Cl less than optimum for soil samples 60 cm deep (Zhang 2000). This means that in the topsoil where wheat roots are abundant, the nutrient is below optimum level. According to this report, in the surface soil (15 cm), 98% of the samples showed response to Cl fertilization. Another 2-year and three-site study in Oklahoma showed an inconsistent response of wheat grain yield to applied Cl (Zhang and Raun 2004).

In today's wheat production in Oklahoma, farmers use mainly N and phosphorus (p) fertilizers that do not have Cl. The practice of avoiding fertilizers containing metallic salts of Cl shows possible deficiency of Cl in soils for crop requirements, especially in high-yielding deep sandy soils with low organic matter (LaRuffa et al. 1999). According to the National Atmospheric Deposition Program (NADP), Cl deposition has been decreasing by 0.04 kg ha^{-1} annually since 1983 (NADP 2003) as a result of various measures to reduce pollution. This indicates that Cl as a micronutrient needs to be studied for cropping systems and soil conditions of a given agro-ecology. Additionally, few studies were conducted to assess the effect of Cl on uptake of N by wheat. With this in mind, long-term Cl experiments were initiated in 1995 at two locations in different soils in Oklahoma to assess the response of winter wheat grain yield and N uptake to Cl fertilizer.

MATERIALS AND METHODS

Two experiments were conducted from 1996 to 2002 at Hennessey (Shellabarger sandy loam–fine loamy, mixed, thermic Udic Argiustolls) and Perkins (Teller sandy loam–fineloamy, mixed, thermic Udic Argiustolls), Oklahoma, to evaluate the response of winter wheat grain yield and N uptake to Cl fertilizer. The Hennessey location is a typical environment for wheat production in north central Oklahoma. The Perkins location is on a deep, sandy, low-organic-matter soil, which is more prone to leaching of mobile nutrients including Cl in soil solution. Initial soil test data are reported in Table 1. A one-to-one soil-to-water paste was used to extract initial soil Cl (Diamond 1994) and was quantified using a Lachat (Milwaukee, WI) flow injection analyzer.

A randomized complete block experimental design with three replications was used at both sites with three rates of 0, 15, and 30 kg Cl ha^{-1} using calcium chloride ($CaCl_2$). Plot sizes were 4.9 m by 6.1 m.

The winter wheat variety Tonkawa was used during the 1996 to 1999 cropping seasons. This variety was replaced by Custer from 2000 to 2002. Wheat was planted between October and November for all experiments at a seeding rate of 98 kg ha^{-1}. All other crop management practices were carried out as per the recommendation of the respective sites. Wheat was

Table 1. Initial soil chemical characteristics at Hennessy and Perkins sites in Oklahoma

Location	pH	NH_4-N (mg kg^{-1})	NO_3-N (mg kg^{-1})	P (mg kg^{-1})	K (mg kg^{-1})	Cl (mg kg^{-1})	
Hennessey	5.8	19	14	142	674	12	12[a]
Perkins	6.0	5	4	51	143	6	5[a]

Notes: Samples were collected from the surface (0–15 cm) except for chloride, where additional samples were analyzed from the entire 0–60 cm depth.

pH and Cl, 1:1 soil–water extraction. NH_4-N and NO_3-N, 2 M KCl extraction. P and K, Mehlich III extraction.

[a]Soil chloride level in the 0–60-cm depth.

harvested from the center of each plot in June with a Massey Ferguson 8XP plot combine, removing an area of 2.0 m by 6.1 m. A Harvest Master yield-monitoring computer installed on the combine recorded yield data, and sub-samples were collected. Grain samples were dried in a forced-air oven at 66°C, ground to pass a 140-mesh sieve (100 μm), and analyzed for total N content using a Carlo-Erba 1500 dry combustion analyzer.

Grain yield data were subjected to statistical analysis using SAS (SAS Institute 2001). Polynomial orthogonal contrasts were used to detect trends in grain yield or N uptake in response to Cl levels.

RESULTS AND DISCUSSION

Grain Yield

Chloride rates significantly increased wheat grain yield in 50% of the year–site combinations (Tables 2 and 3). At Hennessey in 1998, a quadratic trend

Table 2. Effect of chloride fertilizer ($CaCl_2$) on wheat grain yield (Mg ha^{-1}) at Hennessey, Oklahoma

Parameter	1996	1997	1998	1999	2000	2001	2002	Average
Cl: 0 Kg ha^{-1}	2.47	2.07	4.10	2.31	4.25	2.20	3.50	3.00
Cl: 33.6 Kg ha^{-1}	2.40	2.17	4.50	2.33	4.23	2.11	3.89	3.06
Cl: 67.2 Kg ha^{-1}	2.42	2.66	4.29	2.10	4.04	2.44	3.99	3.13
SED contrast	0.18	0.50	0.14	0.20	0.13	0.10	0.40	0.09
Linear	NS	NS	NS	NS	NS	*	NS	NS
Quadratic	NS	NS	*	NS	NS	NS	NS	NS

Notes: NS, not significant. *, **, significant at the 10%, 5% levels, respectively. SED: standard error of the difference between two equally replicated means.

Table 3. Effect of chloride fertilizer ($CaCl_2$) on wheat grain yield (Mg ha^{-1}) at Perkins, Oklahoma

Parameter	1996	1997	1998	1999	2000	2001	2002	Average
Cl: 0 Kg ha^{-1}	1.16	0.63	1.62	0.86	1.21	2.18	2.78	1.49
Cl: 33.6 Kg ha^{-1}	1.22	0.66	1.61	0.89	1.47	2.16	2.92	1.56
Cl: 67.2 Kg ha^{-1}	1.47	0.83	1.92	1.12	1.67	2.06	2.87	1.71
SED contrast	0.12	0.07	0.19	0.13	0.16	0.13	0.14	0.06
Linear	*	**	NS	*	**	NS	NS	**
Quadratic	NS	NS	NS	NS	NS	NS	NS	NS

Notes: NS, not significant. *, **, significant at the 10%, 5% levels, respectively. SED: standard error of the difference between two equally replicated means.

was observed. The response at Hennessey in 1998 showed a common response trend of mobile nutrients such as Cl. In 2001, wheat grain yield increased linearly with an increase in Cl levels. Even though not significant, an increasing linear trend in grain yield was observed at Hennessey in 1997 as well as in 2002. In contrast, in 2000 a decrease in yield was observed with an increase in Cl rate. The average increment in grain yield (cf. no Cl check) averaged over years was only 2 and 4%, respectively for 33.6 and 67.2 kg ha^{-1} Cl rates. The increase in grain yield for some of the years might be attributed to nitrification inhibition in soils where pH was low as reported by previous research (Christensen and Brett 1985; Roseberg, Christensen, and Jackson 1986). The conditions that induce Cl response of crops in soils such as Hennessey are primarily rainfall and pH. The initial soil Cl levels both on the surface (0–15 cm) and at a depth of 0–60 cm (Table 1) were slightly lower than that required for optimum yield. This explains the irregularity in response observed at this location.

At Perkins, wheat grain yield was significantly influenced in four years (1996, 1997, 1999, and 2000) and the average of all years. In all cases, a linear response was observed where yield was increased with an increase in Cl rate. Over years, 33.6 and 67.2 kg ha^{-1} Cl fertilization resulted in 5.0 and 14.5% increment in grain yield. The fact that this site is characterized by a sandy loam soil might explain the linear response to Cl. The initial soil test level of 6.0 mg kg^{-1} at this site was way below the 13.2 mg kg^{-1} required for optimum grain yield when Cl is the most limiting nutrient. This partially explains why significant responses to Cl were obtained at Perkins. As an anion, Cl is not readily adsorbed on the soil exchange complex or organic matter and mostly present in the soil solution. Because of this, Cl moves readily with soil water and is more prone to loss in sandy soils. This results in a quick depletion of Cl deposited in the soil, resulting in deficiency and subsequent response of wheat to applied Cl.

Table 4. Effect of chloride fertilizer ($CaCl_2$) on grain N uptake (Kg ha^{-1}) at Hennessey, Oklahoma

Parameter	1996	1997	1998	1999	2000	2001	2002	Average
Cl: 0 Kg ha^{-1}	77.6	68.4	107.3	58.6	99.4	54.9	98.0	80.9
Cl: 33.6 Kg ha^{-1}	77.2	73.8	120.6	57.7	99.5	56.0	109.3	83.8
Cl: 67.2 Kg ha^{-1}	74.6	86.6	115.6	52.2	99.3	62.6	108.7	85.7
SED contrast	5.5	15.8	4.7	5.3	8.3	3.3	10.8	2.9
Linear	NS	NS	NS	NS	NS	NS	NS	*
Quadratic	NS	NS	*	NS	NS	**	NS	NS

NS, not significant. *, **, significant at the 10%, 5% levels, respectively. SED: standard error of the difference between two equally replicated means

The results from this site clearly shows that sandy loam soils in Oklahoma need to be supplemented with Cl especially if potassium is inherently available and if calcium is not applied to the soils, because the fertilizer form of these two nutrients contain Cl. This is an important part of wheat management because farmers tend to supply wheat mainly with N and P fertilizers and not potassium, leading to Cl deficiency in those soils. The results obtained here are also in agreement with previous research reports (Thomason et al. 2001; Koening and Pan 1996; Zhang 2000).

Grain Nitrogen Uptake

Chloride levels affected this variable in 2 of 7 years at Hennessey, in 1 of 7 years at Perkins (Tables 4 and 5), and the average of years at both locations. In 2001 at Hennessey and in 2000 at Perkins, a significant linear response in grain N uptake was obtained with increasing rates of Cl, while a quadratic response was obtained at Hennessy in 1998. In 1996 and 1999 at Hennessey, the N uptake decreased linearly but insignificantly with

Table 5. Effect of chloride fertilizer ($CaCl_2$) on grain N uptake (Kg ha^{-1}) at Perkins, Oklahoma

Parameter	1996	1997	1998	1999	2000	2001	2002	Average
Cl: 0 Kg ha^{-1}	28.6	N/A	29.1	17.8	21.2	54.4	66.0	35.7
Cl: 33.6 Kg ha^{-1}	28.2	N/A	31.1	19.3	26.0	55.3	70.4	38.4
Cl: 67.2 Kg ha^{-1}	36.0	N/A	36.8	21.3	29.8	52.8	69.2	41.0
SED contrast	4.5	N/A	5.6	3.3	4.0	3.1	5.0	1.4
Linear	NS	N/A	NS	NS	*	NS	NS	**
Quadratic	NS	N/A	NS	NS	NS	NS	NS	NS

Notes: NS, not significant. *, **, significant at the 10%, 5% levels, respectively. SED: standard error of the difference between two equally replicated means.

increasing Cl application rates, whereas N uptake increased linearly in 1998 and 1999 at Perkins. Although significant differences in N uptake due to Cl fertilization were found only in 3 of the 14 experiments, 7 experiments showed a linear increase, and 5 of them showed an increasing and then a decreasing quadratic response. Overall, application of 33.6 and 67.2 kg ha^{-1} Cl at the Hennessey site resulted in 3.5 and 5.6% grain N uptake, respectively, compared with the no Cl check. At Perkins, the two Cl rates resulted in 7.5 and 14.8% increase in grain N uptake. This suggests that Cl has a direct or indirect effect on N uptake by wheat crop. This could be due to an antagonistic effect of Cl on NO_3^- in the leaf tissue, which might have affected N uptake in grain as reported by previous research (Christensen and Brett 1985). The physiological basis of this response, however, needs to be further studied.

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