The Effects of Chloride and Potassium Nutrition on Seed Yield of Annual Canarygrass

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ABSTRACT

The year-to-year variability of seed yield in annual canarygrass (*Phalaris canariensis* L.) is a major concern among growers. A field experiment was conducted at 13 site-years across Saskatchewan to determine the response of annual canarygrass seed yield to K and Cl, and to provide better recommendations to producers on the use of KCl fertilizer in annual canarygrass based on soil test results. Potassium did not affect the yield or development of annual canarygrass over a range of 155 to 717 kg K ha^{-1} in the top 15 cm of soil. Chloride had a large impact on annual canarygrass seed yield; seed yield increased by approximately 24% when Cl was added in the form of KCl or $CaCl_2$ when averaged across all sites. The seed yield increased because the application of Cl increased panicle size (seeds panicle^{-1}). The magnitude of the response tended to increase as level of Cl in the soil decreased. Annual canarygrass growers need to measure Cl when using soil tests to determine fertilizer requirements. It is recommended that 9.1 kg Cl ha^{-1} in the form of 20 kg ha^{-1} of KCl be applied when the Cl level in the surface soil (0–15 cm) is below 70 kg Cl ha^{-1}. The findings encourage growers to conduct individual field test strips to determine the strength of the Cl response.

Historically, the greatest use for annual canarygrass seed has been as bird food. Approximately 69 to 79% of the world's annual canarygrass is produced in Canada (FAO, 2008). Production of annual canarygrass in North America is centered in the province of Saskatchewan (FAO, 2008). Annual canarygrass was first tested as a grain crop in 1906 at Indian Head, SK, (MacKay, 1907). In Canada, recording the area seeded to annual canarygrass began in 1971 with 800 ha and the seeded acreage has ranged from 95,000 to 350,000 ha over the last 20 yr, with 89 to 98% of this production occurring in Saskatchewan (Saskatchewan Ministry of Agriculture, 2008).

Annual canarygrass growers identified spatial and temporal variability in seed yield as their greatest concern in an informal survey (May, 1998). The survey was conducted by separately interviewing between 26 individual farmers at their homes or after meetings. The most common comment from growers was the large amount of biomass being produced in certain years with very little seed being harvested. Research on various agronomic practices which include seeding date, seeding rate, insect, disease and weed control and fertility on annual canarygrass seed yield has been conducted over the years (Holt and Hunter, 1987; Holt, 1988,1989; Miller, 2000; May, 2002; May et al., 2012). May et al. (2012) and Miller (2000) found that seeding date affected seed yield and could account for some but not all of the seed yield variability reported by growers. Seeding rate has also been examined and there was a modest increase in seed yield of 12.5% in one study (Holt, 1989), and 8.5% in a second study (May et al., 2012). In the second study, the increase in seed yield was combined with increased yield stability as seeding rate increased (May et al., 2012). Weed control is important in preventing a large decrease in seed yield (Holt and Hunter, 1987); however, weed control issues did not appear to be a major cause of the observed variation in seed yield reported by farmers. Disease control is important in annual canarygrass and appears to account for some of this seed yield variability (May, 2002).

The effects of N fertility on annual canarygrass have been studied. Holt (1988) found over a 6-yr period at Indian Head, SK, that seed yield was maximized between 50 and 75 kg N ha^{-1}, increasing yield by 43% to 1680 kg ha^{-1}. This study was conducted using a conventional tillage system and N rates between 0 and 100 kg N ha^{-1}. May et al. (2012) in a study conducted across Saskatchewan, found that grain yield was maximized at 78 kg N ha^{-1} increasing seed yield by 7% to 1216 kg ha^{-1}. This study was conducted in a no-till system evaluating N rates ranging from 20 to 100 kg N ha^{-1}. Nitrogen does not have a large enough effect to account for the reported yield variation (May, 1998).

Very little information has been published on the requirements of annual canarygrass for K and Cl. Putnam et al. (1996) published K recommendations for annual canarygrass in North

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Abbreviations: LV, latent variables; NDVI, normalized difference vegetative index; PLS, partial least squares projection to latent structures; VIP, variable importance in the projection.

Dakota. In a study examining the effects of K and S, KCl had a large effect on seed yield at specific locations while S had no effect on seed yield of annual canarygrass (May, 2002). The response could not be correlated with K levels in the soil, and Cl levels in the soil were not tested.

Potassium is an osmotically active element associated with cell expansion, enzymes activation, and regulation of stomata (Amtmann et al., 2008; Romheld and Kirkby, 2010). Potassium is also involved in photosynthesis, phloem loading, uptake and transport, and the storage of assimilates. Potassium deficiency can be manifested in many ways including, slow growth, lower yield, lodging, increased susceptibility to fungal and bacterial diseases and increased sensitivity to drought (Beaton and Sekhon, 1985; Amtmann et al., 2008; Romheld and Kirkby, 2010).

The effect of Cl has been not studied in annual canarygrass; however, Cl is involved in several plant functions, including, enzyme activation, photosynthesis, nutrient transport, stomatal activity, accelerated plant development, and improved disease suppression (Fixen,1993). The effect of Cl has been studied in wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.), and oat (*Avena sativa* L.), but the results have varied between studies. Mohr et al. (1995a, 1995b) found an inconsistent response in the grain yield in wheat and barley to Cl. Fixen (1993) found that the grain yield of spring wheat responded to Cl and published a chart on when to apply Cl to spring wheat based on soil residual Cl. In wheat and barley, cultivars have differed in their response to Cl (Mohr et al., 1995a, 1995b; Grant et al., 2001; Evans and Riedell, 2006). When researchers have found an effect of Cl they have attributed the response to several factors including, osmoregulatory functions, interactions with other nutrients, interaction with diseases and alteration of crop development (Fixen, 1993). Many of the studies could not identify the reason for the observed effect of Cl in increasing grain yield (Fixen et al., 1986; Engel et al., 1994; Gaspar et al., 1994; Diaz-Zorita et al., 2004).

The objectives of the study were to determine if K or Cl or both are responsible for any effects on seed yield of annual canarygrass and possibly help to explain the reported temporal variability in seed yield. Field experiments were conducted to determine the responsiveness of annual canarygrass on seed yield to K and/or Cl, and to provide better recommendations to producers on the use of KCl in annual canarygrass using soil test results.

MATERIALS AND METHODS

A field experiment was conducted at four areas in Saskatchewan, Canada Indian Head (50°33’08.37” N, 103°38’39.82” W and elevation 579 m), Carry The Kettle (2 sites) (50°24’56.59” N, 103°34’47.13” W and elevation 642 m, 50°24’46.98” N, 103°35’39.29” W and elevation 616 m), Regina plain in 2007 (50°20’59.67” N, 104°47’20.50” W and elevation 576 m) in 2008 and 2009 (50°08’13.17” N, 104°21’41.51” W and elevation 580 m) and Stewart Valley (50°34’26.94” N, 107°49’30.99” W and elevation 722 m) from 2007 to 2009. The soil series were Indian Head heavy clay (Orthic Vertisol or Haplocryert) at Indian Head, an Oxbow loam (Orthic Black Chernozem or Udic Boroll) and Ellisboro (Rego Black Chernozem or Udic Boroll) at Carry The Kettle, Regina heavy clay (Orthic Vertisol or Haplocryert) on the Regina plain and Sceptre heavy clay (Orthic Vertisol or Haplocryert) at Stewart Valley. To differentiate between the two sites near Carry The Kettle when needed they will be called CTK ellisboro and CTK loam. The site at Stewart Valley in 2008 was not used due to a salinity and moisture gradient that was parallel to the replicates that created considerable variability among plots. The experiment was conducted at Indian Head only in 2008 and 2009.

The experiment design used for each site-year was a randomized complete block design involving 10 treatments and four replications. The treatments consisted of a check plot with no K or Cl and three forms of fertilizer, KCl, K_2SO_4, and $CaCl_2$ each applied at three rates (Table 1). The three rates of fertilizer for KCl and K_2SO_4 resulted in 10, 20, and 30 kg K ha^{-1} being applied and three rates of fertilizer for KCl and $CaCl_2$ resulted in 9.1, 18.2 and 27.3 kg Cl ha^{-1} being applied. This resulted in three treatments with 10, 20, and 30 kg K ha^{-1} from K_2SO_4, three treatments with 9.1, 18.2 and 27.3 kg Cl ha^{-1} from $CaCl_2$ and three treatments with the three rates with K and Cl in combination from KCl. KCl is the form of fertilizer used by producers to apply K or Cl. A blanket application of fertilizers was applied to all plots at a rate of 46 kg N ha^{-1} [urea, $CO(NH_2)_2$], 10.9 kg P ha^{-1} (mono-ammonium phosphate, $NH_4H_2PO_4$), 12 kg ha^{-1}of S [ammonium sulfate, $(NH_4)_2SO_4$]. All fertilizers were side banded and placed 2 to 3 cm to the side and 7 to 8 cm below the seed using a hoe opener.

The cultivar CDC Togo was seeded at a rate of 35 kg ha^{-1} at all locations. This cultivar is a glabrous (hairless) type of annual canarygrass. The row width was 30.5 cm at Indian Head, Carry

Table 1. The form and rate of K and Cl used for each treatment.

Treatment	Form	Potassium	Chloride	KCl rate 0–0–60–0†	K_2SO_4 rate 0–0–51–17†	$CaCl_2$ rate (94% pure $CaCl_2$)
		kg ha^{-1}				
1	none	0	0.0			
2	KCl	10	9.1	20.0		
3	KCl	20	18.2	40.0		
4	KCl	30	27.3	60.0		
5	K_2SO_4	10			23.5	
6	K_2SO_4	20			47.1	
7	K_2SO_4	30			70.6	
8	$CaCl_2$		9.1			15.1
9	$CaCl_2$		18.2			30.2
10	$CaCl_2$		27.3			45.3

† The concentration of K in the applied fertilizer is calculated as K_2O.

The Kettle and Regina, and 25.4 cm at Stewart Valley. The plot size was 10.7 by 4.0 m at Indian Head, Carry The Kettle and Regina; and 9.1 by 4.3 m at Stewart Valley. The plots were managed using a no-till production system. Glyphosate [N-(phosphonomethyl) glycine] was applied before seeding and all in-crop broadleaf herbicide applications were determined separately for each location according to weed species and density using recommended products and rates (Saskatchewan Ministry of Agriculture, 2010).

Data Collection

Soil tests were performed at each site for N, P, K, S, and Cl. Spring soil test levels of NO_3– N and Cl were measured to a depth of 60 cm. This was done by collecting soil from a 0- to15-cm depth and a 15- to 60-cm depth. Soil residual P, K, and S were measured in a 0- to 15-cm depth. A $NaHCO_3$ extraction procedure (Hamm et al., 1970) was used to estimate residual soil N (NO_3), P, and K. Available Cl was determined by extraction of 5 g of soil with 50 mL of water followed by filtration and determination of Cl in the filtered extract using a Technicon Auto-analyzer II (Inland Waters Directorate, 1979). Available S was determined by extraction of 10 g of soil with 50 mL of 0.001 M $CaCl_2$ followed by filtration and determination of S in the filtered extract using a Technicon Auto-analyzer II (Hamm et al., 1973).

The bioavailable K supply rates were determined using ion exchange resin membranes probes (Plant Root Simulator [PRS] probes, Western Ag Innovations, Saskatoon, SK, Canada) according to the procedures outlined in Qian and Schoenau (2002) and Qian et al. (2008). This measurement of K availability provided an indication of the supply of readily available K to an adsorbing surface, taking into account replenishment of soil solution K by the solid phase as well as movement by diffusion. The probes were charged by soaking in 0.5 M HCl for 2 to 4 h to saturate the exchange sites with H^+ ions. The cation probes were then inserted directly into a sample of soil at field capacity for 24 h. After 24 h, the probes were removed and washed of all soil particles and placed into a clean self-sealing bag and treated with 20 mL of 0.5 M HCl for 1 h to elute the sorbed K ions from the membrane surface. The eluent was the analyzed for K concentration using flame emission spectroscopy. Using the concentration of K in the eluent and the surface area of the membrane, K supply rate was calculated as μg K sorbed per cm^2 of membrane surface over 24 h.

Plant density was determined 3 to 5 wk after seeding and annual canarygrass panicles were counted after panicle emergence. Both plants and panicles were measured in two 1-m sections of crop row within each plot. Physiological maturity was reached when kernel moisture was approximately 30 to 35%. Lodging was rated in each plot at physiological maturity using a scale of 1 to 10 (1 = standing, 10 = completely lodged). At each location, the mean normalized difference vegetative index (NDVI) from each plot was measured between stem elongation and flag leaf using a handheld optical sensor (RT 100, GreenSeeker, NTech Industries, Ukiah, CA) (NTech Industries, 2009). The NDVI is a vegetation index that is an indirect measure of the crops aboveground biomass and nutrient uptake (Moges et al., 2004; Freeman et al., 2007; Osborne, 2007). Significant correlations between NDVI and grain yield have been obtained in winter wheat (Raun et al., 2001), corn (*Zea mays* L.; Teal et al., 2006), soybean [*Glycine max* (L.) Merr.; Ma et al., 2001], spring wheat (Osborne, 2007), grain sorghum [*Sorghum bicolor* (L.) Moench subsp. *bicolor;* Moges et al., 2007; Tucker and Mengel, 2008] and canola (*Brassica napus* L.; Holzapfel et al., 2009). The GreenSeeker optical sensor determines NDVI by actively emitting radiation in the visible red (~660nm) and near infrared (~770nm) bandwidths and measuring the proportion of emitted radiation that is reflected from the canopy. The sensor's field of view is approximately 60-cm wide and NDVI is calculated using the following relationship, NDVI = (NIR – red)/(NIR + red), where red and NIR are the spectral reflectance measurements for the visible red and near-infrared regions, respectively. Depending on the plot length, approximately 30 to 70 individual NDVI values were logged for each plot and the average of these was used to represent the plot.

Seed yield was expressed on a clean seed basis and was corrected to a uniform kernel moisture content of 13%. Kernel weight, expressed per 1000 seeds (g), was calculated by weighing between 700 and 1000 kernels with the number of kernels determined using an automated seed counter. Kernel panicle^{-1} was calculated using panicles m^{-2}, seed yield, and kernel weight. Kernel m^{-2} was calculated using seed yield and kernel weight. Test weight was measured as specified by the Canadian Grain Commission's Official Grain Grading Guide (2011).

Statistical Analysis

A combined analysis was conducted using the MIXED procedure in SAS (Littell et al., 2006). The effect of replicate and site (location × year combinations) were considered random, and the effects of applied treatments were considered fixed. A combination of variance estimates and P values were used to determine the importance of the random sites by fixed effects interaction. Treatment effects were declared significant at $P \leq 0.05$.

We then examined important site × treatment interactions. The first portion of this analysis considered the quantitative relationships between crop yield (dependent variable) vs. site and environment indicators using the partial least squares projection to latent structures (PLS) method. Data for the PLS analysis consisted of a matrix with each site as a row (site means were used for crop dependent variables), and the site and environment indicators as columns. The PLS analysis was performed using the PROC PLS procedure of SAS (Tobias, 1995; SAS Institute, 2005). Initially, all site and environment indicators measured in the study were included as predictor variables in the PLS model. Predictors with the greatest influence in explaining dependent variable variability, or variable importance in the projection (VIP), were then selected based on the criterion of VIP > 0.8 (Wold, 1994). It was found that three PLS latent variables (LV) typically explained close to 80% or more of the variation for the predictor and response variables. The X loadings represent the correlation between raw data for each of the site and environment predictors to the scores for each LV. These X loadings were used to assess the relative importance of each of the site and environment predictors toward each of the three LVs. The LV scores were

Table 2. Soil residual levels of Cl, K, N, P and S at the start of the each field experiment.

Year	Location	Cl 0–15 cm	Cl 0–60 cm	K 0–15 cm	K supply rate 0–15 cm	K supply rate 15–30 cm	N 0–60 cm	P 0–15 cm	S 0–15 cm
		kg Cl ha^{-1}		kg K ha^{-1}	µg K cm^{-2}		kg N ha^{-1}	kg P ha^{-1}	kg S ha^{-1}
2007	Stewart Valley	18.3	76.3	466	10.8	5.0	37.8	41.2	6.6
	CTK ellisboro	15.7	57.3	155	5.9	4.0	25.5	29.6	5.2
	CTK loam	14.7	49.3	246	8.4	4.8	36.9	19.4	5.6
	Regina plain	16.0	84.2	528	4.9	3.6	54.9	19.0	22.3
2008	Indian Head	90.8	242	508	4.0	1.3	79.3	10.9	11.1
	CTK ellisboro	36.2	168	207	8.3	3.1	26.9	27.7	5.3
	CTK loam	47.8	224	310	7.2	2.6	56.6	21.7	7.7
	Regina plain	70.4	376	512	3.1	2.0	31.1	5.4	6.4
2009	Indian Head	72.9	215	717	5.4	3.3	28.7	25.7	52.2
	Stewart Valley	66.4	213	465	8.7	2.7	50.2	54.8	66.4
	CTK ellisboro	42.6	176.	303	10.6	2.7	28.1	25.6	4.2
	CTK loam	42.7	138	303	8.3	2.3	52.9	21.3	17.1
	Regina plain	44.7	358	576	3.0	1.6	39.8	7.5	6.2

used for the second portion of the analysis to further examine important site × treatment interactions for response variables of interest.

The second portion of this analysis, which used LV scores and original data, was conducted to determine reasons for important site × crop/cultivar treatment interactions determined from the initial univariate mixed model analysis of variance. Scores for each LV were merged with the original data set including crop yield. This meant there was a single score available for each site × LV combination. An extension of the previously described mixed model was implemented to explore site interactions with treatments (Littell et al., 2002). A covariable (LV) × treatment interaction was included in the model statement to determine if treatment differences varied as the LV scores varied across sites. For those LVs that resulted in a significant ($P < 0.05$) LV score × treatment interaction, means were estimated at the lowest, average, and highest level of the LV scores. X loadings for significant LV interactions were used to infer environment/climate predictors responsible for the covariable × treatment interaction.

A grouping methodology, as previously described by Francis and Kannenberg (1978), was used to further explore treatment responses among sites. The mean and CV were estimated for each level of the treatment of interest across remaining treatments, sites, and replicates. Means were plotted against CV for each treatment combination, and overall mean of the treatments means and CVs was included in the plot to categorize the data into four categories: Group I: High mean, low variability (optimal); Group II: High mean, high variability; Group III: Low mean, high variability (poor); and Group IV: Low mean, low variability.

RESULTS AND DISCUSSION

Soil and Environmental Conditions

The soil residual nutrient levels in the soil before seeding at each location are presented in Table 2. A wide range of fields

Table 3. Summary of climatic conditions and percentage of the 30-yr long term average from May first to August 31st for experimental sites in Saskatchewan in 2007–2009.

Location/year	Precipitation May	June	July	August	Percent of 30-yr long-term average	Air temperature May	June	July	August	Percent of 30-yr long-term average
	mm					°C				
Indian Head										
2008	21	60	90	47	86	9	14	17	18	92
2009	15	60	59	77	83	8	14	14	15	81
Long-term average	56	79	67	53		11	16	18	18	
Stewart Valley										
2007	67	53	34	29	72	12	16	23	18	106
2008	98	138	91	97	168	13	15	18	18	98
2009	12	51	61	61	73	10	15	17	17	91
Long-term average	56	76	69	52		12	16	19	18	
Carry the Kettle										
2007	83	47	51	65	110	11	15	20	16	98
2008	7	81	96	39	99	9	14	17	13	81
2009	20	57	42	105	100	8	14	14	15	81
Long-term average	43	87	49	45		11	16	18	18	
Regina plain †										
2007	63	24	22	49	67	11	16	22	16	100
2008	8	69	75	80	99	10	13	18	18	91
2009	38	50	45	78	90	9	16	16	16	88
Long-term average	53	75	64	43		12	16	19	18	

† Bratts Lake is the closest environmental station to this location.

Table 4. Statistical analysis of all sites combined.

Source	Plant density	Head density		Panicle size	Seed density	Kernel weight	Grain yield	Height	NDVI†	Test weight
	plants m^{-2}	panicles plant^{-1}	panicles m^{-2}	seeds panicle^{-1}	seeds m^{-2}	g 1000 kernels^{-1}	kg ha^{-1}	cm	0–1	g 0.5 L^{-1}
	P value									
Treatment	0.880	0.466	0.888	**<0.001**‡	**<0.001**	0.079	**<0.001**	0.703	0.261	0.081
K × Cl	0.890	0.546	0.907	0.832	0.661	0.594	0.674	0.562	0.849	0.951
Cl rate	0.288	0.104	0.593	**0.009**	**0.001**	0.439	**0.001**	0.405	0.152	0.104
Cl linear	0.192	0.043	0.382	**0.015**	**0.002**	0.584	**0.004**	0.716	0.570	0.052
Cl quadratic	0.189	0.266	0.293	0.076	**0.022**	0.137	**0.015**	0.311	0.066	0.119
K rate	0.583	0.092	0.412	0.807	0.763	0.809	0.739	0.578	0.213	0.747
K linear	0.185	0.054	0.099	0.538	0.937	0.916	0.860	0.424	0.479	0.524
K quadratic	0.675	0.107	0.772	0.686	0.681	0.416	0.806	0.250	0.082	0.691
	Variance estimate									
Site (S)	4,789.7	0.7778	20,489.7	167.0	70,713,785	0.1587	432529.9	578.7	0.0178	260.1
Treatment × S	130.9	0.0256	–23.1	5.942	2,586,908	0.0221	20266.5	–0.5059	–1.9E-05	657.9
	Variance estimate *P* value									
S	0.017	0.018	0.016	0.016	0.015	0.022	0.015	0.015	0.050	0.074
Treatment × S	0.149	0.201	0.932	**<0.001**	**<0.001**	**0.011**	**<0.001**	0.655	0.910	**<0.001**
	Percentage of total variance									
Treatment × S§	3	3	0	3**	4**	12*	4**	0	0	72**

* Significance at 0.05 probability level.

** Significance at the 0.01 probability level.

† NDVI, normalized difference vegetative index.

‡ *P* values were bolded when they were less than 0.05.

§ This is the percentage of the total variance that is associated with effect of site. Treatment × S variance estimate/(Treatment × S variance estimate + S variance estimate) × 100.

with Cl and K levels were found. No fields were found that were low in K and high in Cl. Growing season precipitation and average temperatures are presented in Table 3. Precipitation was more than 10% above average at Carry the Kettle in 2007 and Stewart Valley in 2008 and precipitation was at least 10% below average at Indian Head in 2008 and 2009, Stewart Valley in 2007 and 2009, and Regina plain in 2007 and 2009. At all locations, the average temperature for the growing season was below110% of the 30-yr average for that site. On the other hand, the temperature was 90% or less of the 30-yr average for several locations and years including Indian Head in 2009, Carry The Kettle in 2008 and 2009, and the Regina plain in 2009. During this study, temperature tended to be near average or below average at the sites where the experiment was conducted.

Crop Development and Seed Yield

When the data was averaged across all locations the application of K or Cl had no effect on the plant density or panicle density of annual canarygrass (Table 4) and plant density and panicle density were at a level that would not restrict the yield potential of annual canarygrass (Table 5). Plant height was not affected by the application of K or Cl. The height of the annual canarygrass was between 86 and 87 cm for all treatments. The NDVI was measured before the flag leaf was visible and the application of K or Cl had no effect on NDVI. The NDVI of the annual canarygrass ranged from 0.4537 to 0.4925 for all 10 treatments. The major disease that affects annual canarygrass, septoria leaf mottle (*Septoria triseti*), was not affected by K or Cl. There were no visible differences observed from the application of K or Cl before heading. In winter wheat, Engel et al. (1994) observed that there were visible differences in plant development between the boot and flowering stages.

Table 5. The effect of Cl and K on the development and seed yield of annual canarygrass.

Fertilizer treatment	Plant density	Panicle density		Panicle size	Seed density	Kernel weight	Seed yield	Test weight
kg K and Cl ha^{-1}	plants m^{-2}	panicles plant^{-1}	panicles m^{-2}	seeds panicle^{-1}	seeds m^{-2}	g 1000 kernels^{-1}	kg ha^{-1}	g 0.5 L^{-1}
0K-0Cl	260	2.7	581	21.7	12,641	7.81	991	315
10K-9.1Cl	274	2.3	597	25.3	15,428	7.95	1227	338
20K-18.2Cl	272	2.4	594	25.6	15,020	7.91	1189	339
30K-27.3Cl	267	2.5	600	26.0	15,561	7.99	1231	342
10K-0Cl	268	2.4	589	20.8	12,159	7.74	952	315
20K-0Cl	274	2.4	599	21.4	12,865	7.79	1015	326
30K-0Cl	274	2.4	608	20.6	12,381	7.81	961	319
0K-9.1Cl	268	2.4	590	25.8	15,384	7.94	1226	341
0K-18.2Cl	276	2.4	600	25.2	15,216	7.93	1202	341
0K-27.3Cl	269	2.4	597	26.1	15,758	7.87	1235	340
LSD 0.05	ns†	ns	ns	2.6	1,468	ns	126	ns

† ns, not significant.

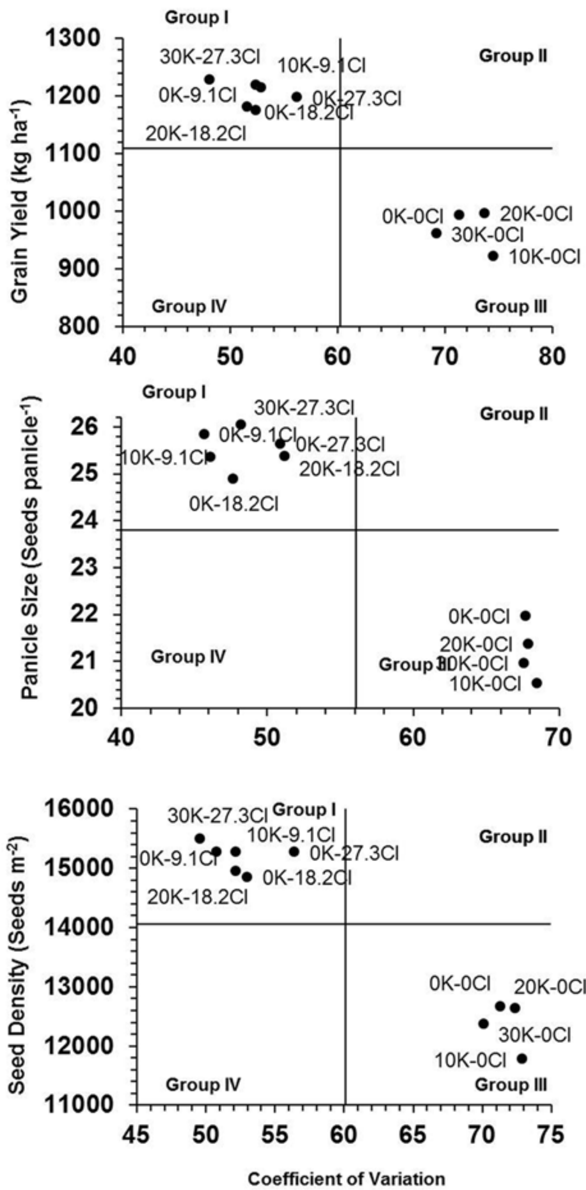

Fig. 1. Biplot [estimated means vs. coefficient of variation (CV)] of the 10 treatments for data collected from six sites over 3 yr in Saskatchewan from 2007 to 2009. Group I: High mean, low variability (optimal); Group II: High mean, high variability; Group III: Low mean, high variability (poor); Group IV: Low mean, low variability.

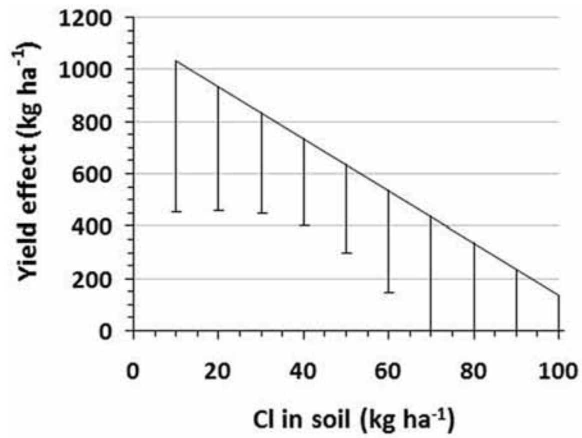

Fig. 2. Sensitivity analysis of seed yield in annual canarygrass to soil Cl levels in a 0- to 15-cm depth. Yield effect is the difference between the average seed yield of treatments 8, 9, and 10 vs. entry 1. Error bars that cross horizontal axis indicate those effects/differences not different from zero.

Panicle size (seeds panicle^{-1}) and seed density (seeds m^{-2}) were affected by the application of Cl but not by K (Table 4). Panicle size (seeds panicle^{-1}) showed a linear response to increases in rate of Cl and seed density (seeds m^{-2}) showed a curvi-linear response with increasing rates of Cl. The form of Cl used did not affect the response of annual canarygrass to Cl (Table 5). Kernel weight was not affected by the application of Cl or K. Therefore, the main yield component that was affected by the addition of Cl was panicle size (seeds panicle^{-1}). The Cl appears to have helped the annual canarygrass fertilize more ovules or retain seed during the reproductive development of annual canarygrass. A similar response was observed in a specific hard red spring wheat cultivar, Marshall, with an increase in seed density and not kernel weight (Evans and Riedell, 2006). This cultivar appears to take up less Cl than other wheat cultivars at a given Cl concentration in sand culture (Evans and Riedell, 2006). Other research found that kernel weight and not seed density was the yield component that was increased in cereals (Gaspar et al., 1994; Engel et al., 1994).

There was a curvi-linear increase in seed yield to the application of Cl but not K (Table 4). Averaged across all sites, seed yield increased by approximately 24% when Cl was added in the form of KCl or CaCl2 (Table 5). The lowest Cl rate used in the study, 9.1 Cl kg ha^{-1} was sufficient to increase yield and no responses to higher rates of Cl were observed. A response curve cannot be accurately calculated since the response occurred between two rates 0 and 9.1 kg Cl ha^{-1}. In previous research reporting seed yield responses to Cl, yields tended to increase over a wider range of Cl rates (Fixen et al., 1986; Engel et al., 1994).

The form of Cl did not matter, with both KCl and $CaCl_2$ being equally effective in increasing seed yield (Table 5). This lack of sensitivity to the form of Cl has also been observed in wheat (Fixen et al., 1986; Mohr et al., 1995b) and barley (Mohr et al., 1995b). When the means of seed yield, panicle size (seeds panicle^{-1}) and seed density (seeds m^{-2}) were plotted against the coefficient of variation it became clear that all the rates of Cl evaluated increased yield and reduced yield variability (Fig. 1). Test weight followed a similar trend as seed yield; however the linear contrast had a P value of 0.052 (Tables 4 and 5).

The interaction between the treatments and site was significant for seed density, kernel weight, seed yield, and test weight (Table 4). Seed density (seeds m^{-2}) deviated from the overall means at CTK loam 2008, CTK ellisboro 2009, Indian Head 2008, and Regina plain 2008. For the two CTK site-years, the response to Cl was larger than the over all response while at the other two locations the response to Cl was smaller than when averaged over all the sites (Table 6). This site response to Cl for seed density (seeds m^{-2}) resulted in three sites, CTK loam 2008, CTK ellisboro 2009, and Regina plain 2008, having seed yield treatment means which deviated from the overall treatment means. The seed yield response to Cl was larger at CTK loam 2008 and CTK ellisboro 2009 and smaller at Regina plain 2008. CTK ellisboro 2009, the site-year with the largest response to Cl was the only location where all treatment means for this site deviated from the overall

Table 6. Deviation of the site means from the overall mean of seed density, seed yield, and test weight.

	Treatments									
	1	2	3	4	5	6	7	8	9	10
	KCl				K_2SO_4			$CaCl_2$		
Location/year	0K-0Cl	10K-9.1Cl	20K-18.2Cl	30K-27.3Cl	10K-0Cl	20K-0Cl	30K-0Cl	0K-9.1Cl	0K-18.2Cl	0K-27.3Cl
	Seed density (no. m^{-2})									
	12,641	15,428	15,020	15,561	12,159	12865	12381	15,384	15,216	15,758
	(Deviations; no. m^{-2})									
CTK loam 2007	–1,397	364	1,348	776	–900	–1659	–1520	594	1,241	852
CTK loam 2008	–2,222*	3,441**	829	–1,537	–1,202	–308	–2686**	1,911	262	1,847
CTK loam 2009	646	–938	–321	–432	583	948	–193	–801	329	446
CTK ellisboro 2007	603	–281	–511	–694	990	533	754	–678	–357	–848
CTK ellisboro 2008	–1371	517	591	484	–961	–1157	–950	806	1258	404
CTK ellisboro 2009	–3336**	1934	2,664**	1,924	–3593**	–3599**	–2516*	2198*	1,883	2,255*
Indian Head 2008	2,024*	–1521	–167	189	429	1947	1371	–949	–2,105*	–860
Indian Head 2009	1021	–2006*	–340	–854	947	582	1834	–1,126	269	141
Regina plain 2007	763	48	–979	570	913	209	464	–955	–549	–615
Regina plain 2008	2,144*	126	–362	–171	874	292	527	159	–967	–2,470*
Regina plain 2009	756	–508	–1696	–163	1,066	1110	839	–820	–800	354
Stewart Valley 2007	807	–623	–675	–661	926	1353	741	–339	–853	–786
Stewart Valley 2009	–438	–553	–381	569	–74	–250	1334	–1	388	–719
	Seed yield (kg ha^{-1})									
	991	1227	1189	1231	952	1015	961	1226	1202	1235
	(Deviations; kg ha^{-1})									
CTK loam 2007	–132	28	124	83	–85	–158	–136	47	112	88
CTK loam 2008	–157	286**	–39	–141	–101	–44	–303**	289**	–20	264**
CTK loam 2009	67	–86	0	–46	47	79	–4	–59	–26	60
CTK ellisboro 2007	55	–32	–48	–61	88	44	75	–69	–33	–68
CTK ellisboro 2008	–103	21	24	54	–72	–102	–61	54	114	32
CTK ellisboro 2009	–307**	170*	254**	202*	–331**	–334**	–216*	171*	172*	203*
Indian Head 2008	147	–70	4	–36	72	143	124	–97	–130	–129
Indian Head 2009	87	–145	–11	–84	75	137	125	–65	32	–99
Regina plain 2007	78	11	–82	75	53	20	54	–109	–64	–50
Regina plain 2008	180*	–13	–34	–51	84	39	69	–31	–49	–182*
Regina plain 2009	57	–75	–105	–4	110	104	105	–86	–78	–17
Stewart Valley 2007	73	–49	–60	–54	81	107	51	–38	–69	–54
Stewart Valley 2009	–44	–46	–27	62	–21	–35	118	–7	38	–48

* Significance at 0.05 probability level.

** Significance at the 0.01 probability level.

treatment means. At this site, the addition of Cl increased test weight (data not shown). It is interesting to note that this site did not have the lowest level of Cl (Table 2). When the site × treatment interaction for kernel weight was examined, no clear trend emerged with just one site mean in 1 yr deviating from the overall means (data not shown).

Soil Chloride Levels and Seed Yield

To determine the suitability of using soil test measurements for recommending the application of Cl, a partial least squares analysis was performed (principal component analysis with a regression component added). Variable importance for the projection was generated for Cl in the 0- to 15-cm depth, of 2.01 and for Cl in the 0- to 60-cm depth of 1.68. This indicated that the 0- to 15-cm depth was more consistent in predicting the responsiveness of annual canarygrass to the application of Cl. A sensitivity analysis was performed indicating that once the level of residual Cl in the soil reached 70 kg ha^{-1} in the 0- to 15-cm depth, the effect of applying Cl became insignificant ($P = 0.074$; Fig. 2). Therefore, soils with levels below 70 kg Cl ha^{-1} in the 0- to15-cm depth should receive Cl when annual canarygrass is grown. More data would improve the accuracy of this recommendation. This may indicate that annual canarygrass is more sensitive to a Cl deficiency than other cereal crops. Fixen (1993) found that soil Cl levels needed to be below 50 kg ha^{-1} in a 0- to 60-cm depth to elicit a seed yield increase in wheat with the application of Cl fertilizer, while this study indicates that Cl fertilizer should be applied when Cl levels drop below 70 kg ha^{-1} in the 0- to 15-cm depth. In addition, at the site with the largest seed yield response to Cl in annual canarygrass, CTK ellisboro, no response to Cl was found in wheat when preliminary studies on wheat and annual canarygrass were conducted in the same year (Lafond, 2001; May, 2002). Annual canarygrass may be a suitable species to use to investigate the effects of Cl on reproductive development in plants.

CONCLUSIONS

The response of annual canarygrass seed yield to Cl occurred under low or high yielding conditions. The yield component that was responsible for the yield increase was panicle size (seeds $panicle^{-1}$). No response was observed to K even in fields where the residual levels were low to moderate in K according to soil test extractable K and soil K supply rate. Annual canarygrass growers are advised to measure Cl when doing soil tests. It is recommended that 9.1 Cl kg ha^{-1} in the form of 20 kg ha^{-1} of KCl be applied when the Cl level in the soil (0–15 cm) is below 70 kg Cl ha^{-1}. Annual canarygrass appears to be more sensitive to Cl deficiency than wheat.

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REFERENCES

Amtmann, A., S. Troufflard, and P. Armengaud. 2008. The effect of potassium nutrition on pest and disease resistance in plants. Physiol. Plant. 133:682–691. doi:10.1111/j.1399-3054.2008.01075.x

Beaton, J.D., and G.S. Sekhon. 1985. Potassium nutrition of wheat and other small grains. In: R.D. Munson, editor, Potassium in agriculture. ASA, CSSA, and SSSA, Madison, WI. p. 701–752.

Canadian Grain Commission. 2011. Official Grain Grading Guide, 7.1–7.24 http://www.grainscanada.gc.ca/oggg-gocg/01/oggg-gocg-1-eng.htm (accessed 4 Aug. 2011).

Diaz-Zorita, M., G.A. Duarte, and M. Barraco. 2004. Effects of chloride fertilization on wheat (Triticum aestivum L.) productivity in the sandy Pampas region, Argentina. Agron. J. 96:839–844. doi:10.2134/agronj2004.0839

Engel, R.E., J. Eckhoff, and R.K. Berg. 1994. Grain yield, kernel weight, and disease response of winter wheat cultivars to chloride fertilization. Agron. J. 86:891–896. doi:10.2134/agronj1994.00021962008600050025x

Evans, K.M., and W.E. Riedell. 2006. Responses of spring wheat cultivars to nutrient solutions containing additional potassium chloride. J. Plant Nutr. 29:497–504. doi:10.1080/01904160500526493

FAO. 2008. Food and Agriculture Organization of the United Nations. http://faostat.fao.org. (accessed 25 Jan. 2012).

Fixen, P.E. 1993. Crop responses to chloride. Adv. Agron. 50:107–150. doi:10.1016/S0065-2113(08)60833-0

Fixen, P.E., G.W. Buchenau, R.H. Gelderman, T.E. Schumacher, J.R. Gerwing, F.A. Cholick, and B.G. Farber. 1986. Influence of soil and applied chloride on several wheat parameters. Agron. J. 78:736–740. doi:10.2134/agronj1986.00021962007800040035x

Francis, T.R., and L.W. Kannenberg. 1978. Yield stability studies in short-season maize. I. A descriptive method for grouping genotypes. Can. J. Plant Sci. 58:1028–1034.

Freeman, K.W., D.B. Arnall, R.W. Mullen, K. Girma, K.L. Martin, R.K. Teal, and W.R. Raun. 2007. By-plant prediction of corn forage biomass and nitrogen uptake at various stages using remote sensing and plant height measures. Agron. J. 99:530–536. doi:10.2134/agronj2006.0135

Gaspar, P.E., D.L. Reeves, T.E. Schumacher, and P.E. Fixen. 1994. Oat cultivar response to potassium chloride on soils testing high in potassium. Agron. J. 86:255–258. doi:10.2134/agronj1994.00021962008600020009x

Grant, C.A., D.L. McLaren, and A.M. Johnston. 2001. Spring wheat cultivar response to potassium chloride fertilization. Better Crops 85:20–23.

Hamm, J.W., J.R. Bettany, and E.H. Halstead. 1973. A soil test for sulphur and interpretative criteria for Saskatchewan. Commun. Soil Sci. Plant Anal. 4:219–231. doi:10.1080/00103627309366441

Hamm, J.W., F.G. Radford, and E.H. Halstead. 1970. The simultaneous determination of nitrogen, phosphorus and potassium in sodium bicarbonate extracts of soils. In: Technicon International Congress, Advances in Automatic Analysis, Industrial Analysis, Vol. II:65–69.

Holt, N.W. 1988. Effect of nitrogen fertilizer on the agronomic performance and seed quality of annual canarygrass. Can. J. Plant Sci. 68:41–45. doi:10.4141/cjps88-004

Holt, N.W. 1989. Effects of row spacing and seeding rate on the agronomic performance of annual canarygrass. Can. J. Plant Sci. 69:1193–1198. doi:10.4141/cjps89-141

Holt, N.W., and J.H. Hunter. 1987. Annual Canarygrass (Phalaris canariensis) tolerance and weed control following herbicide application. Weed Sci. 35:673–677.

Holzapfel, C.B., G.P. Lafond, S.A. Brandt, P.R. Bullock, R.B. Irvine, M.J. Morrison, W.E. May, and D.C. James. 2009. Estimating canola (Brassica napus L.) yield potential using an active optical sensor. Can. J. Plant Sci. 89:1149–1160. doi:10.4141/CJPS09056

Inland Waters Directorate. Water Quality Branch. 1979. Analytical methods manual. Natl. Water Quality Data Bank 17203. Environ. Canada, Information Serv., Ottawa, Canada.

Lafond, G.P. 2001.The effects of potassium chloride to counter the negative effects of urea side banded on plant establishment using different placement configurations and soil types, Final Report, Indian Head Research Farm, Indian Head, SK, Canada.

Littell, R.C., G.A. Milliken, W.W. Stroup, and R.D. Wolfinger. 2006. SAS System for mixed models. 2nd ed. SAS Inst., Cary, NC.

Littell, R.C., W.W. Stroup, and R.J. Freund. 2002. SAS for linear models. 4th ed. SAS Inst., Cary, NC.

Ma, B.L., L.M. Dwyer, C. Costa, E.R. Cober, and M.J. Morrison. 2001. Early prediction of soybean yield from canopy reflectance measurements. Agron. J. 93:1227–1234. doi:10.2134/agronj2001.1227

MacKay, A. 1907. Experimental farm for Saskatchewan. In: Ministry of Agriculture, editor, Government of Canada, Ottawa, Canada. p. 338–375.

May, W.E. 1998. Canaryseed research in 1998. Indian head Agricultural Research Foundation, Newsletter, June 1998, p. 4. Indian Head Agric. Res. Foundation, Indian Head, SK.

May, W.E. 2002. The effect of seeding date, seeding rate, and applied nitrogen on the yield of canaryseed. Saskatchewan Agriculture Development Fund, Regina, SK, Canada. http://www.agriculture.gov.sk.ca/ADF/search (accessed 5 Jan. 2012).

May, W.E., G.P. Lafond, Y.T. Gan, P. Hucl, C.B. Holzapfel, and A.M. Johnston. 2012. Yield variability in Phalaris canariensis L. due to seeding date, seeding rate and nitrogen fertilizer. Can. J. Plant Sci. 92:651–669.

Miller, P.R. 2000. Effect of varying seeding date on crop development, yield and yield components in canaryseed. Can. J. Plant Sci. 80:83–86. doi:10.4141/P99-047

Moges, S.M., K. Girma, R.K. Teal, K.W. Freeman, H. Zhang, D.B. Arnall, S.L. Holtz, B.S. Tuban, O. Walsh, B. Chung, and W.R. Raun. 2007. In-season estimation of grain sorghum yield potential using a hand-held optical sensor. Arch. Agron. Soil Sci. 6:617–628. doi:10.1080/03650340701597251

Moges, S.M., W.R. Raun, R.W. Mullen, K.W. Freeman, G.V. Johnson, and J.B. Solie. 2004. Evaluation of green, red, and near infrared bands for predicting winter wheat biomass, nitrogen uptake, and final grain yield. J. Plant Nutr. 27:1431–1441. doi:10.1081/PLN-200025858

Mohr, R.M., D.N. Flaten, C.C. Bernier, and G.J. Racz. 1995a. Effect of chloride fertilization on Bedford barley and Katepwa wheat. Can. J. Soil Sci. 75:15–24. doi:10.4141/cjss95-004

Mohr, R.M., D.N. Flaten, C.C. Bernier, and G.J. Racz. 1995b. Effect of cultivar on response of wheat and barley to chloride fertilization. Can. J. Soil Sci. 75:25–34. doi:10.4141/cjss95-005

NTech Industries. 2009. GreenSeeker RT100 Handheld Sensor. NTech Industries, Inc. http://www.greenseeker.com/RT100-handheld.html (accessed 11 Aug. 2011).

Osborne, S.L. 2007. Utilization of existing technology to evaluate spring wheat growth and nitrogen nutrition in South Dakota. Commun. Soil Sci. Plant Anal. 38:949–956. doi:10.1080/00103620701277916

Putnam, D.H., P.R. Miller, and P. Hucl. 1996. Potential for production and utilization of annual canarygrass. Cereal Foods World 41:74–83.

Qian, P., and J.J. Schoenau. 2002. Practical applications of ion exchange resins in agricultural and environmental soil research. Can. J. Soil Sci. 82:9–21. doi:10.4141/S00-091

Qian, P., J.J. Schoenau, and N. Ziadi. 2008. Ion supply rates using ion exchange resins. In: M. Carter and E. Gregorich, editors, Soil sampling and methods of analysis. 2nd ed. CRC Press, Boca Raton, FL. p. 135–140.

Raun, W.R., J.B. Solie, G.V. Johnson, M.L. Stone, E.V. Lukina, W.E. Thomason, and J.S. Schepers. 2001. In-season prediction of potential grain yield in winter wheat using canopy reflectance. Agron. J. 93:131–138. doi:10.2134/agronj2001.931131x

Romheld, V., and E.A. Kirkby. 2010. Research on potassium in agriculture: Needs and prospects. Plant Soil 335:155–180. doi:10.1007/s11104-010-0520-1

SAS Institute. 2005. The GLIMMIX procedure. SAS Inst., Cary, NC.

Saskatchewan Ministry of Agriculture. 2008. Agricultural statistics. Saskatchewan Ministry of Agric. www.agr.gov.sk.ca/apps/agriculture_statistics (accessed 15 Aug. 2011).

Saskatchewan Ministry of Agriculture 2010. 2010 Guide to crop protection. Saskatchewan Ministry of Agric. http://www.agriculture.gov.sk.ca/ (accessed 15 Aug. 2011).

Teal, R.K., B. Tubana, K. Girma, K.W. Freeman, D.B. Arnall, O. Walsh, and W.R. Raun. 2006. In-season prediction of corn yield potential using NDVI at various vegetative growth stages. Agron. J. 98:1488–1494. doi:10.2134/agronj2006.0103

Tobias, R.D. 1995. An introduction to partial least squares analysis. In: Proceedings Annual SAS Users Group International Conference, 20th, Orlando, FL. 2–5 Apr. 1995. SAS Inst., Cary, NC. www.sas.com/rnd/app/papers/pls.pdf (accessed 25 May 2010). p. 1250–1257.

Tucker, D., and D. Mengel. 2008. The use of active optical sensors to manage N fertilization of sorghum in Kansas. In: A. Schlegel, editor, Great Plains Soil Fertility Conference Proceedings, Denver, CO. 4–5 March. Kansas State Univ., Manhattan. p. 166–177.

Wold, S. 1994. PLS for multivariate linear modeling. In: H. van de Waterbeemd, editor, QSAR: Chemometric methods in molecular design: Methods and principles and principles in medicinal chemistry. Verlag-Chemie, Weinheim, Germany. p. 195–218.