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ABSTRACT

Grass tetany is a complex metabolic disorder that causes substantial livestock production losses and deaths in temperate regions of the world. It is caused by low levels of Mg or an imbalance of K, Ca, and Mg in forage consumed by animals. Development of grasses with improved mineral balance would be an economical means of minimizing losses from this malady. This study was conducted to determine if genetic variability exists among crested wheatgrasses, *Agropyron cristatum* (L.) Gaertner and *A. desertorum* (Fisher ex Link) Schultes, for forage Mg, Ca, K, Fe, Zn, Mn, Cu, Na, and P concentrations. Forage of spaced plants of 10 diverse crested wheatgrass strains was harvested from replicated plots at Lincoln and Alliance, NE, which differ markedly in climate, and analyzed for these minerals. There were genetic differences among strains over locations for Ca, Mg, and Fe concentration in the forage. There were differences among strains within locations but not over locations for K. Strain differences in Zn, Mn, Cu, Na, and P concentrations of the forage were not significant ($P > 0.05$) when averaged over locations. Calcium and Mg were positively correlated ($r = 0.40$). These results indicate that it should be possible to breed crested wheatgrass with increased Mg and Ca concentrations in its forage, thus reducing grass tetany potential.

CRESTED WHEATGRASS is a genetic complex comprised of several species. The most important species in North America are *A. cristatum* and *A. desertorum*, which are diploids and tetraploids, respectively (Asay and Dewey, 1983; Barkworth and Dewey, 1985). In this paper, these two species will be referred to as crested wheatgrass, as they are in commerce.

Crested wheatgrass, which is utilized primarily by ruminants, does not contain significant amounts of any antiquality factor or toxic compounds except for occasionally high levels of nitrates (Mayland, 1986). Ruminant livestock grazing crested wheatgrass in the spring, however, can be severely affected by grass tetany (hypomagnesemic tetany), which can result in livestock deaths and production losses (Mayland, 1986). Thirty percent of all livestock losses attributed to grass tetany in the USA are thought to occur in animals grazing crested wheatgrass (Mayland, 1986).

Grass tetany is a nutritional ruminant disease caused by a deficiency of Mg. It is a complex disease because of interactions of Ca, K, inorganic P, vitamin D, and parathyroid hormone in the ruminant (Littledike and Cox, 1979; Littledike and Goff, 1987). High K levels in the diet reduce Mg absorption (Littledike and Cox, 1979). Milk fever (parturient hypocalcemia), which is due primarily to low availability of Ca to the ruminant, particularly during the initial stages of lactation, is often associated with grass tetany in lactating animals (Littledike and Cox, 1979; Littledike and Goff, 1987). Calcium, Mg, and K levels and the ratio K/(Mg + Ca), in which elements are expressed as equivalents kg^{-1}, are used to estimate the grass tetany potential of grass herbage.

Genetic variability for the concentration of these mineral elements and the K/(Ca + Mg) ratio in grass forage has been reported for tall fescue (*Festuca arundinaceae* Schreber) (Nguyen and Sleper, 1981), reed canarygrass (*Phalaris arundinaceae* L.) (Hovin et al., 1978), and perennial ryegrass (*Lolium perenne* L.) (Sleper, 1979). Hides and Thomas (1981) demonstrated that it was possible to alter the Mg content of Italian ryegrass (*Lolium multiflorum* Lam.) by breeding. Mayland and Asay (1989) demonstrated the existence of genetic variability among 12 clones of *A. desertorum* and among 16 of the 18 original clones of 'Hycrest' crested wheatgrass for Mg, Ca, K, and K/(Ca + Mg) in a study at Logan, UT. Broad-sense heritability estimates were determined from the replicated clones.

The objectives of this study were to: (i) determine if genetic variability exists among crested wheatgrass strains for the concentration of K, Ca, Mg, Fe, Zn, Mn, Cu, Na, and P in their forage, (ii) obtain preliminary estimates of the magnitude of genotype × environment interaction effects, and (iii) determine the correlation of mineral element concentrations with other important agronomic traits.

MATERIALS AND METHODS

The crested wheatgrass and the field cultural procedures used in this study were described previously (Lamb et al., 1984; Vogel et al., 1984.) In brief, 42 crested wheatgrass strains representative of the array of germplasm available to breeders were grown in space-planted nurseries at Lincoln and Alliance, NE during the period 1979 to 1981. The Lincoln and Alliance experiments were located on a Kennebec soil (fine-silty, mixed, mesic, Cumulic Hapludoll) and a Keith soil (fine-silty, mixed, mesic, Aridic Arguistoll), respectively. Alliance is located 540 km west of Lincoln at about the same latitude. Its growing season is 40 d shorter than at Lincoln (120 vs. 160 d) and its annual precipitation is half that of Lincoln (400 vs. 740 mm). The specific climatic conditions at both locations during the study were described by Lamb et al. (1984).

Plots were single rows of 10 spaced plants with plants and rows spaced 1 m apart. The experimental design at both locations was a randomized complete block with four replicates. Plants in both nurseries were harvested for forage yield and sampled for forage quality in 1980 and 1981 after anthesis. Ten of the strains were harvested on an individual plant basis to obtain estimates of within-strain variation while the remaining strains were harvested on a plot basis. The strains harvested on an individual plant basis were used in this study. They included the released cultivars Nordan (tetraploid) and Ruff (diploid), six plant introduction (PI) lines (two tetraploids and four diploids), and two experimental lines (tetraploids). PI 370645 and PI 401003 are tetraploids and PIs 314596, 325180, 369167 and 369170 are diploids. One of the experimental lines, NE 10b-1, is a clonal line that was vegetatively propagated from a single plant of

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'Nebraska 10'. The strains selected for individual plant harvest were the superior strains in the nurseries based on visual evaluations in 1980 before the first harvest. At Lincoln, individual plants were harvested with hand sickles, while at Alliance they were cut with a plot mower. Harvest height was 13 cm at both locations. Forage subsamples (200 g fresh weight) for quality and mineral element analyses were dried in forced air ovens at 65 °C, ground in a Wiley mill through a 1-mm screen, and stored in sealed plastic vials. Samples from both years and locations were used to determine dry matter content, in vitro dry matter digestibility (IVDMD), and protein concentration. Results of those analyses are reported by Lamb et al. (1984). Only the 800 1981 samples, 400 from each location, were used for the mineral analyses.

Forage subsamples were transferred to 75- by 135-mm paper envelopes and dried at 40 °C for about 24 h prior to analysis. Nitric-perchloric acid (3:1) digestion of 0.5 g forage subsamples preceded analysis for Ca, Cu, Fe, K, Mg, Mn, Na, P, and Zn. Phosphorus was measured colorimetrically using the vanadomolybdate procedure. Potassium was determined by flame emission. All other elements were measured by atomic adsorption spectrophotometry. Samples for K, Ca, and Mg were prepared in 0.1% lanthanum (La) prior to analysis. A standard plant sample was included as a check on analytical procedures. Recovery of the National Bureau of Standards citrus leaves (NBS-1572) was 99, 98 and 98% for Ca, Mg and K, respectively. Recovery of the other analyzed elements averaged 101%. All 800 samples were analyzed for Ca, Mg, K, and Fe. Two hundred samples (two or three plants per plot) were analyzed for the complete mineral profile. The cation ratios K/Mg and K/(Mg + Ca) were calculated on an equivalents kg^{-1} basis.

The mean value for the plants in a plot was determined for all traits and the data set of these mean values was used in analyses of variance (ANOVA) for each location and in the across-locations ANOVA to test for strain differences and the significance of the strain × locations effect. Strains, replications, and locations were considered to be random effects in all standard analyses. Variances due to strains (σ_g^2), the interaction of locations and strains (σ_{gl}^2), and error (σ_e^2) and their standard errors were calculated from the mean squares of these ANOVAs using standard methods (Becker, 1984). The phenotypic variance (σ_p^2) was calculated as $\sigma_p^2 = \sigma_g^2 + \sigma_{gl}^2 + \sigma_e^2$.

Estimates of the variation within strains (σ_w^2) were also determined for K, Ca, Mg, and the two ratios described previously. An ANOVA was conducted for all strains within a location using all the individual plant data. One strain was then deleted and the ANOVA was repeated on the modified data set. The within-strain sum of squares for the deleted strain was determined by subtracting the within-strain sum of squares of the deleted data set from the within-strain sum of squares of the complete individual plant data set. The within strain variance for the deleted data set was determined by simply dividing the within-strain sum of squares by the within-strain degrees of freedom for that strain. This process was repeated for all 10 entries for both locations for a total of 22 ANOVAs for each trait.

Pearson correlation coefficients were determined among all traits using individual plant data from both locations (Steel and Torrie, 1960).

RESULTS AND DISCUSSION

Genetic Variation Among Strains

There were genetic differences among the crested wheatgrass strains for forage K concentrations (Table 1). However these differences were small when averaged across locations probably because of a significant genotype × location (G × L) interaction effect, i.e., the strains did not rank similarly in K concentration at the two locations.

There were genetic differences among the strains for Ca content at Lincoln and averaged across locations, although the differences were small at Alliance. Genetic differences existed among the crested wheatgrass strains for Mg, Fe, and the ratio K/Mg at both locations and averaged across locations. There were significant ($P < 0.05$) genetic differences among the strains for P and the ratio K/(Ca + Mg) only at Lincoln. The strains did not differ for Zn, Mn, Cu, and Na concentration of the forage averaged over locations. Genotype × location effects were not significant ($P > 0.05$) except for K and Fe and the ratio K/(Ca + Mg) indicating that, except for these elements and ratio, the relative genetic differences among crested wheatgrass strains for mineral content were similiar at the two locations.

The G × L interaction effect for the ratio K/(Ca + Mg) was probably significant because of the effect of K. It is recognized that the genotype × environment interaction results are based on the minimum number of environments. These environments, however, differed markedly (Lamb et al., 1984).

The mean and range values for the forage mineral element concentrations for Lincoln and Alliance are summarized in Table 2. Recommended mineral concentrations of forages for ruminants vary with age, sex, and physiological condition of the animals (NAS/NRC, 1976; Reid and James, 1985; Working Party on Nutrient Requirements of Ruminants, 1980). Recommendations on minimium mineral element concentrations needed for ruminants also vary somewhat with authority, but all authorities agree that lactating animals have the highest mineral requirements. In terms of mineral requirements of a lactating beef cow (*Bos taurus*), the mineral element concentrations of the crested wheatgrass forage harvested at Lincoln and Alliance can be classified as follows: K, adequate; Ca, adequate to low; Mg, inadequate; P, inadequate; Fe,

Table 1. Summary of analyses of variance for mineral element concentrations of crested wheatgrass grown at Lincoln and Alliance, NE.

	Statistical significance of mean squares			
	Strains			G × L†
Mineral element	Lincoln	Alliance	Across locations	Across locations
K	**	**	NS‡; $P = 0.07$	**
Ca	**	NS; $P = 0.11$	*	NS
Mg	**	**	**	NS
P	*	NS	NS	NS
K/(Ca + Mg)	**	NS; $P = 0.07$	NS	*
K/Mg	**	**	**	NS; $P = 0.08$
Fe	*	**	*	*
Zn	NS	NS	NS	NS
Mn	NS	NS	NS	NS
Cu	NS	NS	NS; $P = 0.06$	NS
Na	NS	*	NS	NS

*,** Indicates significance at the 0.05 and the 0.01 levels of probability, respectively, based on an F test.
† G × L = Strain × location interaction effect.
‡ NS = Not significant at $P = 0.05$ based on an F test.

adequate; Zn, adequate; Mn, adequate; Cu, adequate to low; Na inadequate.

The K/(Ca + Mg) ratio should be 2.2 or less for the forage to be "safe" in terms of its potential for inducing grass tetany in lactating cows (Sleper, 1979). The K/(Mg + Ca) ratio at both locations was less than this critical level (Table 2). The ratio K/(Ca + Mg) estimates the forage's potential to induce either hypomagnesemic tetany or parturient hypocalcemia or both in ruminants, while K/Mg is more applicable to hypomagnesemic tetany. Appropriate values for the K/Mg ratio have not been established. The mineral element concentration of forages change during the growing season and their availability to animals also changes with maturity. Available Mg is generally larger and the K/(Mg + Ca) ratios are usually lower for grasses harvested at heading than for grasses harvested earlier in the growing season (Mayland and Grunes, 1979). The minimum recommended level for Mg is 1.5 to 2.0 g kg^{-1}. Hence, the mean and range values in Table 2 indicate that the Mg, P, and Na levels of crested wheatgrass forage need to be improved to meet the requirements of lactating beef cows.

The among-strain genetic variances (σ^2_g) for Na and P were zero (Table 3). The genetic variances for all the other elements were greater than zero but they were low for Zn, Mn, and Cu. The ratio σ^2_g/σ^2_p (genotypic to phenotypic variance) provides an estimate of the proportion of the among-strain variation attributable to genetic effects. This ratio is similiar to a heritability estimate but the term heritability is inappropriate because the strains are not the progeny of a reference population. The σ^2_g/σ^2_p ratio was greater than 0.30 for K, Ca, Mg, Fe, and K/Mg (Table 3). The ratio was 0.50 for Mg indicating that a substantial proportion of the total variation among strains for Mg was due to genetic effects. The σ^2_{gl} effect for K was almost as large as the σ^2_g effect, which again indicates that the concentration of this element in crested wheatgrass strains relative to other strains varies considerably with environments. Thus, of the three elements that are deficient in crested wheatgrass forage, only Mg appears to be amenable to improvement by selection among strains. The Ca content of crested wheatgrass forage, which is low, could also be improved by selection among strains.

Within Strain Variation

The variance among plants within strains (σ^2_w) was determined for each strain at each location for K, Ca, Mg, K/(Ca + Mg), and K/Mg (Table 4). The within-strain variance, σ^2_w, for the clonal line, NE 10b-1, consisted entirely of plant-to-plant environmental variation and experimental error, while for the other strains it consisted of the same factors plus the within-strain genetic variance among plants. Comparison of σ^2_w of NE 10b-1 with σ^2_w of the other lines thus provides an estimate of the proportion of the variation among plants of a strain that are due to genetic differences among plants. Although it seems reasonable to assume that the among-plant environmental variance and experimental error of the plants propagated by seed would be the same as for the clonal line, it cannot be tested with the available data. Hence we can only draw general inferences from the within-strain variances.

Table 2. Mean and range values for mineral element concentrations and mineral element ratios in forage of crested wheatgrass strains grown at Lincoln and Alliance, NE.

Mineral element	Lincoln		Alliance	
	$\bar{X}$ ± SE	Range	$\bar{X}$ ± SE	Range
	g kg^{-1}			
K	15.3 ± 0.5	12.7–17.6	11.1 ± 0.5	10.0–12.8
Ca	2.7 ± 0.1	2.2–3.3	2.8 ± 0.2	2.4–3.2
Mg	1.0 ± 0.1	0.9–1.2	1.0 ± 0.1	0.8–1.2
P	1.6 ± 0.1	1.5–1.8	1.5 ± 0.1	1.4–1.6
	ratios			
K/(Ca + Mg)	1.8 ± 0.1	1.5–2.3	1.4 ± 0.1	1.0–1.6
K/Mg	4.8 ± 0.2	3.7–6.4	3.8 ± 0.3	2.6–4.7
	mg kg^{-1}			
Fe	247 ± 22	188–297	331 ± 28	235–449
Zn	18 ± 2	15–20	19 ± 3	16–24
Mn	32 ± 4	25–42	44 ± 7	34–58
Cu	3 ± 0.3	2.8–3.6	4 ± 0.3	3.0–4.1
Na	42 ± 6	37–56	36 ± 2	30–40

Table 3. Variance component estimates for mineral element concentrations and mineral element ratios in crested wheatgrass forage from the across locations ANOVA.

Mineral element	Variance components† ± SE‡			
	σ^2_g	σ^2_{gl}	σ^2_e	σ^2_g/σ^2_p
K	1.03 ± 0.73	0.94 ± 0.48	0.88 ± 0.17	0.36
Ca	0.04 ± 0.03	0.01 ± 0.01	0.09 ± 0.12	0.42
Mg	0.01 ± 0.01	0.00 ± 0.01	0.01 ± 0.01	0.50
P	0.0 ± 0.0	0.0 ± 0.0	0.02 ± 0.00	0.00
K/(Ca + Mg)	0.01 ± 0.01	0.01 ± 0.00	0.04 ± 0.01	0.17
K/Mg	0.39 ± 0.19	0.05 ± 0.04	0.23 ± 0.04	0.58
Fe	2191 ± 1310	903 ± 677	2636 ± 498	0.38
Zn	1.8 ± 1.5	0.0 ± 1.6	22.3 ± 4.2	0.08
Mn	1 ± 11	2 ± 16	134 ± 25	0.01
Cu	0.05 ± 0.03	0.0 ± 0.02	0.32 ± 0.06	0.14
Na	0.0 ± 6	4 ± 11	82 ± 15	0.00

† σ^2_g = variance due to strains; σ^2_{gl} = variance due to the interaction of location and strains; σ^2_e = plot error variance; $\sigma^2_p = \sigma^2_g + \sigma^2_{gl} + \sigma^2_e$ = phenotypic variance.

‡ SE of 0.00 indicates SE was <0.005.

At Lincoln, σ^2_w was at least twice as large for all elements and ratios evaluated for the lines propagated by seed as for NE 10b-1 except for the ratio K/Mg for some lines (Table 4). At Alliance, only the variance for Ca was larger for all lines propagated by seed than for the clonal line. Some of the lines propagated by seed at Alliance had larger σ^2_w values than the clonal line for Mg and K/(Ca + Mg). The σ^2_w values at Alliance were higher for the clonal line than for the other strains for K and the ratio K/Mg. These results indicate that there was substantial within-strain genetic variability among strains for the traits evaluated when the strains were grown at Lincoln. However, at Alliance, the within-strain genetic variability among strains was considerably smaller, except for Ca. There was genetic variation within some of the strains for Mg at Alliance. The within-strain genetic variation of crested wheatgrass is probably due to additive effects because of its mating system and the methods used to propagate the strains, and hence could be used to improve the grass in a breeding program.

Breeding Potential

The between-strain genetic variances (Table 3) and the apparent magnitude of the within-strain genetic

Table 4. Within-strain variation (σ_w^2) for 'Ruff', 'Nordan', NE 10b-1 (a clonal line), and seven PI or experimental crested wheatgrass strains.

Location/strain	K		Ca		Mg		K/(Ca + Mg)		K/Mg	
	$\bar{X}$	σ_w^2	$\bar{X}$	σ_w^2	$\bar{X}$	σ_w^2	$\bar{X}$	σ_w^2	$\bar{X}$	σ_w^2
	g kg^{-1}						ratio			
Lincoln										
Ruff	17.1	5.53	2.2	0.16	1.1	0.02	2.3	0.43	5.1	2.64
Nordan	14.5	4.38	2.9	0.36	1.0	0.02	1.7	0.15	4.9	1.22
Range of PI or exp. strains†		2.40–9.01		0.20–0.79		0.01–0.04		0.12–1.00		0.50–1.62
NE 10b-1	17.6	1.64	3.3	0.10	0.9	0.00†	1.9	0.04	6.4	0.48
Alliance										
Ruff	11.0	2.21	2.7	0.26	1.0	0.03	1.4	0.09	3.7	0.68
Nordan	11.2	2.61	3.0	0.32	0.9	0.01	1.3	0.09	3.9	0.67
Range of PI or exp. strains‡		0.91–5.36		0.15–0.39		0.01–0.04		0.02–0.11		0.15–0.81
NE 10b-1	11.7	5.88	3.0	0.08	0.8	0.02	1.5	0.06	4.9	0.98

† Range of means are listed in Table 2.
‡ σ_w^2 was <0.005.

Table 5. Correlations of mineral element concentrations, mineral element ratios, and other traits of crested wheatgrass forage when harvested after head emergence.†

Traits	Ca	K	Mg	Fe	Zn	Mn	Cu	Na	P	K/Mg	K/(Ca+Mg)
K	0.02										
Mg	0.40**	0.10**									
Fe	0.16**	−0.21**	0.26**								
Zn	0.25**	−0.02	0.05	0.17*							
Mn	0.39**	−0.33**	0.19**	0.36**	0.56**						
Cu	0.21**	0.00	0.15*	0.13	0.18**	0.26**					
Na	0.10**	0.08	0.11	0.02	−0.05	−0.07	0.07				
P	0.15*	0.29**	0.07	−0.04	0.29**	0.05	0.12	−0.05			
K/Mg	−0.22**	0.73**	−0.56**	−0.33**	−0.02	−0.35**	−0.08	−0.01	0.17*		
K/(Ca + Mg)	−0.54**	0.76**	−0.33**	−0.30**	−0.08	−0.43**	−0.13	0.00	0.14*	0.84**	
Height	−0.16**	0.15**	−0.35**	−0.47**	−0.04	−0.18*	−0.14*	0.08	0.09	0.33**	0.26**
Yield	−0.25**	0.25**	−0.26**	−0.39**	−0.24**	0.33**	−0.18*	0.05	−0.06	0.35**	0.35**
IVDMD%‡	0.01	−0.06	0.14**	0.15**	−0.16*	0.02	0.12	0.00	−0.10	0.13**	−0.06
Protein %	0.18**	0.64**	0.32**	−0.13**	0.10	−0.18**	0.00	0.13	0.45	0.30**	0.35**
Dry matter %	−0.16**	−0.25**	−0.12**	0.08*	−0.09	−0.04	−0.21**	0.04	−0.20**	−0.14**	−0.09**
Heading date§	0.05	−0.25**	0.24**	0.34**	0.10	0.20**	0.15*	−0.20**	−0.06	−0.34	−0.25**

*,** Indicates significance at the 0.05 and .01 levels of probability, respectively.
† N = 800 for all traits except for Zn, Mn, Cu, Na, and P for which N = 200.
§ Day of the year.
‡ IVDMD = in vitro dry matter digestibility.

variances (Table 4) indicate that it should be possible to breed for improved Ca and Mg concentration in crested wheatgrass by conducting an among- and within-strain breeding program. It may be possible to improve the K/(Ca + Mg) ratio by breeding to improve the Ca and Mg concentration of the forage. It will be very difficult to change the K concentration of the forage for potential cultivars that will be used over a wide geographical area because of the apparent large genotype × environment interaction effects for K content. Attempting to change the K/(Ca + Mg) ratio by breeding only for the K component of the ratio would appear to be difficult. These results are consistent with those reported by Mayland and Asay (1989).

A similar range in values for most elements was found among both the *A. desertorum* and the *A. cristatum* strains. This suggested that ploidy level per se was not an indicator of relative mineral element concentration among crested wheatgrass strains. The Ca and Mg concentration of both types of crested wheatgrass could be improved by breeding.

Calcium was positively correlated with the other minerals tested except for K (Table 5). The highest correlations were with Mg. Calcium was also positively correlated with protein, but its correlation with forage yield was negative. The correlation of Mg with the other elements was positive but often low or not significant, except for Ca. Magnesium was positively correlated with IVDMD and protein but was negatively correlated with yield. The negative correlations of Ca and Mg with forage yield were low ($r \leq 0.26$) but significant ($P < 0.01$). Both Ca and Mg were negatively correlated with the ratios K/(Ca + Mg) and K/Mg, which is highly desirable since low ratios are associated with reduced levels of grass tetany.

CONCLUSION

The results of this study indicate that it should be possible to breed crested wheatgrass for improved Mg and Ca concentration. Selecting for improved Ca and Mg should result in a decreased K/(Ca + Mg) ratio and slightly increased or stable IVDMD and protein content of the forage. Selection for Ca and Mg could result in reduced forage yields unless selection pressure also was applied to forage yields, since Ca and Mg are negatively correlated with forage yield. It does not appear feasible to breed for increased Na and P content of crested wheatgrass forage. Breeding for increased Ca and Mg concentration could result in strains with reduced grass tetany potential, which could result in significant reductions in animal losses for livestock producers.

The results of this study may be criticized since the plants were sampled at a single stage of development.

This was done in order to limit the number of samples that needed to be analyzed, and also to obtain yield estimates. We sampled at anthesis because we reasoned that, by this stage of development, the plants would not be accumulating any significant additional dry matter and the mineral element concentration of the forage would represent an accumulative average of the mineral element concentration for the growing season. In a subsequent grazing study at Mead, NE which is about 45 km north of Lincoln, replicated pastures of Ruff and Nordan crested wheatgrass were sampled during a 6-wk period beginning in April and ending in June for 3 yr. The relative differences in mineral concentration for Ruff and Nordan averaged over the grazing season were similar to those based on sampling at anthesis in this study (K.P. Vogel, B.C. Gabrielsen, J.K. Ward, H.L. Mayland, and B. Anderson, 1988, personal communication). Results reported by Mayland and Asay (1989) and Sleper et al. (1980) also indicate that genetic differences among genotypes of crested wheatgrass and tall fescue, respectively, are relatively consistent over cuttings and environments. Additional studies will have to be conducted to determine the magnitude of the stage-of-growth × genotype interaction effect on mineral element concentration in crested wheatgrass. It is now possible to do this type of study using the strains that we have identified as differing in forage mineral concentration.

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