Alberta Pasture Nutrient Analysis

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Abbreviations

Total Digestible Nutrients	TDN
Crude Protein	CP
Neutral Detergent Fibre	NDF
Calcium	CA
Phosphorus	P
Magnesium	Mg
Potassium	K
Sulphur	S
Copper	Cu
Manganese	Mn
Zinc	Zn
Selenium	Se
Molybdenum	Mo
Iron	Fe
Rocky Mountain House	RMH
Medicine Hat	MedHat

Introduction

During the grazing season, forage must meet the nutritional requirements of beef cattle to support reproduction, lactation, and growth. These nutrient requirements are influenced by a combination of factors including body size, milk production, pregnancy status, and grazing activity (NRC, 1996). Cattle obtain minerals from water, soil, and forages, with the majority of mineral intake typically comes from the forage component of the diet (McDowell, 1996). However, forages alone often do not provide a balanced diet for grazing cattle. Essential trace minerals such as selenium, cobalt, and iodine are not strictly required for plant growth and are therefore often lacking or absent in pasture plants (Liu et al., 2022). Levels of other essential trace minerals including zinc, manganese, and copper are frequently below livestock requirements (McDowell, 1996).

The mineral content of forage is influenced by several interacting factors including soil mineral composition, plant species, plant maturity, environmental conditions, pasture management, and fertilization practices (McDowall, 1996; Jones & Tracy, 2015). Of particular concern is the widespread application of macronutrient fertilizers (N, P, and K), which can enhance forage biomass production without replenishing trace element concentrations in the soil. This practice may exacerbate trace mineral deficiencies in grasslands (McDowall, 1996). Consequently, a comprehensive understanding of region-specific forage mineral profiles is essential for developing effective and sustainable supplementation strategies. This not only helps prevent deficiencies that impair animal performance but also avoids excessive supplementation that increases costs and risks of mineral antagonisms.

Routine analysis of fresh herbage for nutrient composition is not common practice among producers, leaving a gap in practical reference data. To address this need, the present study investigates the macro- and micro-nutrient composition of pastures across Alberta, Canada, from late May to October. The objective is to characterize seasonal and regional variation in forage nutrient content and provide reference values that can help livestock producers make informed decisions regarding mineral supplementation based on the geographic and temporal context of their operations.

Materials and Methods

Sampling for this study was conducted in 2021, 2023, and 2024. The year 2022 was skipped due to funding constraints. The province of Alberta was split into nine regions: Nanton, Medicine Hat, Hanna, Rocky Mountain House (RMH), Red Deer, Mayerthorpe, St Paul, Manning, and La Crete. Within each region, nine pastures were sampled from three farms (three pastures per farm).

Sampling occurred during three periods each year: late May/ early June, August, and October. Each sampling period was two weeks in duration to collect all samples throughout the province.

Grass samples were collected in the same pastures throughout the study; clipping locations were not GPS marked. A minimum of twelve locations were sampled in order to collect a representative sample of what was growing in the pasture. The number of sampling locations was increased when grass was not abundant in order to collect sufficient volume for analysis. Sampling locations were selected in an 'X' pattern to ensure spatial representation. A 10 x 10-inch wooden quadrat was placed on the ground and all grass within the square was clipped to collect a uniform quantity at each location. In May/June and October, grass was clipped at 1.5 inches off the ground, in August the grass was clipped at 4 inches off the ground to collect samples representative of what the cattle were consuming. Grass clippings were placed into paper bags and marked with the region, producer name, and pasture name. Grass height, stage of maturity, type of vegetation (native, tame, or mixed), and whether the pasture was grazed or un-grazed was recorded for each pasture. Stage of maturity was determined by referencing a manuscript titled "Describing and Quantifying Growth Stages of Perennial Forage Grasses" by Moore et al. (1991). Grass samples were air dried at Blue Rock Animal Nutrition (Innisfail, AB). All samples were shipped via courier to A&L Laboratories (London, ON) to be analyzed by wet chemistry for: moisture, total digestible nutrients (TDN), crude protein (CP), neutral detergent fibre (NDF), calcium (Ca), phosphorus (P), magnesium (Mg), potassium (K), sulphur (S), sodium (Na), copper (Cu), manganese (Mn), zinc (Zn), molybdenum (Mo), iron (Fe), acid detergent fibre (ADF), lignin, starch, crude fat, and total ash. Selenium (Se) was analyzed separately in one pasture per producer (three pastures per region). These samples were split and sent to CARO Laboratories (Edmonton, AB) for analysis via ICP-MS. To ensure detection sensitivity, selenium analyses were run undiluted. Pastures comprised of native grass, tame grass, or a mix of both and were representative of the area (Table 1). Grass type (native or tame), height, and stage of growth was recorded for each pasture.

Table 1. Approximate distribution of grass type in pastures sampled in each region.

	% Native	%Tame	% Mix of Native and Tame
La Crete	-	100	-
Manning	-	67	33
St. Paul	-	56	44
Mayerthorpe	-	90	10
Red Deer	33	56	11
RMH*	11	89	-
Hanna	67	-	33
Medicine Hat	27	73	-
Nanton	78	22	-

*RMH = Rocky Mountain House

Statistical Analysis

Statistical analysis was performed in R (version 4.4.2). Prior to analysis, outliers were identified and removed using the interquartile range (IQR) method. Specifically, values falling below Q1 − 1.5 × IQR or above Q3 + 1.5 × IQR were excluded from the dataset to reduce the influence of extreme values.

The data was analyzed using Analysis of Variance (ANOVA) models to assess the effects of sampling time, region, and their interaction on nutrient concentrations. A repeated measures design was employed. Specifically, a mixed-effects ANOVA was conducted with Sampling Time and Region as fixed effects and Field as a random effect to account for the nested structure of the data (repeated measures from each field). The model was fit using the lmer function from the lme4 package, and p-values were obtained using the lmerTest package.

Significant main effects and interactions were assessed, and pairwise comparisons were made using Tukey's Honest Significant Difference test for post-hoc analysis, where appropriate. The results of these tests were adjusted for multiple comparisons using the Bonferroni correction or Tukey method.

Normality of residuals was assessed using Q-Q plots and the Shapiro-Wilk test. Homogeneity of variances was tested using Levene’s test. Where necessary, data were log-transformed to meet model assumptions of normality and homogeneity of variance. Main effects and interactions were considered significant at the 0.05 significance level, and post-hoc comparisons were interpreted using adjusted p-values.

Results & Discussion

Statistically significant differences do not indicate practical significance. It is important to compare values to cattle requirements to determine if a nutrient surplus or deficiency exists.

Statistical analysis was not conducted on acid detergent fibre, lignin, starch, crude fat, and total ash and therefor is not discussed in this manuscript. However, the raw data is available upon request.

Total Digestible Nutrients

Total digestible nutrients were highest in the May sampling period, and lowest in the October sampling period. Sampling time ($p<2e-16$) and region ($p<2e-16$) both had a significant effect on TDN content of pasture grass. The interaction of sampling time and region was also significant ($p = 0.012$) suggesting that the rate at which TDN levels decline is dependent on the region. Varying environmental conditions between years (within regions) did not significantly impact TDN levels ($p = 0.62$).

Total Digestible Nutrients in May

Total Digestible Nutrient concentrations in May ranged from 59.93% ± 3.61 SD in Medicine Hat to 65.98% ± 2.49 SD in Nanton, as shown in Table 2. The relatively low standard errors in most regions (0.55–0.63) suggest the mean TDN values are fairly reliable, though some regional variability in forage quality may still influence animal intake and performance.

Table 2. Mean forage Total Digestible Nutrient concentrations (% DM) by region in Alberta during May sampling, with standard deviation, standard error, and range.

	TDN	Groups	std	se	Min	Max
Nanton	65.98	a	2.49	0.55	61.67	71.33
RMH	65.51	ab	3.04	0.57	60.56	70.49
RedDeer	65.21	abc	2.16	0.57	60.15	68.11
Mayerthorpe	65.06	abc	2.41	0.55	60.16	69.36
Manning	64.63	abc	2.55	0.57	60.30	69.34
Hanna	63.66	abc	4.32	0.56	55.32	71.19
LaCrete	63.41	bc	3.30	0.58	57.51	68.07
StPaul	62.65	cd	1.77	0.70	60.08	66.08
MedHat	59.93	d	3.61	0.63	51.49	64.60

Total Digestible Nutrients in August

Table 3. Mean forage Total Digestible Nutrient concentrations (% DM) by region in Alberta during August sampling, with standard deviation, standard error, and range.

	TDN	Groups	std	se	Min	Max
Manning	61.50	a	2.35	0.57	58.41	67.16
LaCrete	61.34	a	3.02	0.58	56.40	67.04
Mayerthorpe	60.60	a	3.11	0.55	53.15	68.40
StPaul	60.10	ab	3.28	0.70	53.73	64.44
RedDeer	59.90	ab	2.99	0.58	55.35	66.44
RMH	59.61	ab	3.07	0.58	53.34	65.69
Nanton	59.56	ab	2.42	0.56	54.94	64.33
Hanna	57.66	bc	3.91	0.57	50.56	65.86
MedHat	55.98	c	1.95	0.63	52.34	59.38

By August, mean TDN declined across all regions, with values ranging from 55.98% ± 1.95 SD in Medicine Hat to 61.50% ± 2.35 SD in Manning, as shown in Table 3. Increased variability is evident in higher standard deviations (up to 3.91) and standard errors (around 0.57), reflecting heterogeneous forage conditions likely due to differences in pasture management, plant species composition, and environmental factors. This variability should be considered when planning supplementation, as some animals may experience lower-quality forage than the regional mean suggests.

Total Digestible Nutrients in October

Total Digestible Nutrients continued to drop from August to October as forage matured (Table 4). Variability in TDN content between regions was minimal, with most of the province falling into "group a". Medicine Hat was the only region measuring significantly lower in TDN than most of the province at 51.20% DM, and Hanna was not significantly different from any other region of the province at 54.25% DM.

Table 4. Mean forage Total Digestible Nutrient concentrations (% DM) by region in Alberta during October sampling, with standard deviation, standard error, and range.

	TDN	Groups	std	se	Min	Max
RMH	57.25	a	3.45	0.76	50.77	62.94
StPaul	57.25	a	4.11	0.93	52.04	65.90
Nanton	56.61	a	3.18	0.73	49.10	66.67
Mayerthorpe	56.57	a	3.03	0.73	51.80	62.89
LaCrete	56.05	a	4.36	0.79	47.89	66.38
RedDeer	55.87	a	4.43	0.77	48.09	67.34
Manning	55.77	a	4.69	0.77	48.39	66.88
Hanna	54.25	ab	4.87	0.74	48.97	68.41
MedHat	51.20	b	2.63	0.84	46.08	57.37

Effect of Sampling Time on TDN

Table 5. TDN (% DM) loss rate from May to August and August to October.

	TDN (% DM) Loss Rate May to Aug		TDN (% DM) Loss Rate Aug to Oct
Nanton	-8.3	Manning	-5.7
Hanna	-6.0	LaCrete	-5.3
RMH	-5.9	MedHat	-4.8
RedDeer	-5.3	Mayerthorpe	-4.0
Mayerthorpe	-4.5	RedDeer	-4.0
MedHat	-4.0	Hanna	-3.4
Manning	-3.1	StPaul	-2.9
StPaul	-2.6	RMH	-2.4
LaCrete	-2.1	Nanton	-1.1

All changes in TDN from May to August, and August to October were significant ($p < 0.05$) with the exception of La Crete, where the change in TDN from May to August was not significantly different ($p = 0.1$), and in St. Paul from May to August where the change in TDN was borderline significant ($p = 0.053$). Table 5 shows these regions had the lowest change in TDN compared to all other regions of the province.

Total Digestible Nutrients Discussion

Total Digestible Nutrients exhibited a clear and consistent decline across the grazing season in all regions studied. The highest TDN concentrations were observed in May, averaging around 66%, which decreased substantially by August and continued to decline through October, with late-season values often below 57%. The most pronounced TDN losses occurred between May and August, with regions such as Nanton and Hanna experiencing declines greater than 6–8%. From August to October, the rate of TDN loss slowed but remained notable, particularly in regions like Manning and La Crete where losses approached 5–6%.

These seasonal declines in forage energy density are typical as plants mature and lignify, reducing digestibility and the amount of energy available to grazing cattle. The variability in TDN loss rates across regions likely reflects differences in plant species composition, growth stage at sampling, and local environmental conditions such as temperature and moisture.

Meeting the TDN requirements of mid-gestation beef cows is critical to maintain body condition and support fetal development. Literature suggests that these cows require approximately 56–58% TDN in their diet during mid-gestation (Gadberry, 2004). While most regions met or exceeded this threshold in May, by August and especially October, several areas including Medicine Hat and Hanna, consistently fell below these levels. This indicates that supplementation with energy-rich feeds may be necessary in the latter half of the grazing season to prevent energy deficits.

The relatively high variability in TDN concentrations, as indicated by standard deviations and standard errors, suggests that while mean values provide useful guidance, individual animal intake and regional forage quality may vary considerably.

Crude Protein

Our results show crude protein was highest in the May sampling period and declined through August and October. Crude protein was significantly impacted by region ($p<2e-16$), sampling time ($p = 1.73E-09$), the sampling time: region interaction ($p = 8.02E-08$), and year ($p = 7.27E-05$).

Crude Protein in May

Crude protein concentrations in May were relatively high across all regions, with no significant differences among most sites ($p > 0.05$) with the exception of Medicine Hat, which was significantly lower than much of the province. Mean CP levels ranged from 13.15% ± 2.54 SD in Medicine Hat to 16.00% ± 2.13 SD in Mayerthorpe (Table 6).

Standard deviations were moderate (ranging from 1.61% in St. Paul to 3.10% in Hanna), suggesting relatively high variability in CP values within most sites. Overall, May CP values exceeded the dietary requirement of approximately 7–8% for mature beef cows in mid-gestation, suggesting adequate protein supply in early season forage across all regions.

Table 6. Mean forage Crude Protein concentrations (% DM) by region in Alberta during May sampling, with standard deviation, standard error, and range.

	CP	Groups	std	se	Min	Max
Mayerthorpe	16.00	a	2.13	0.39	12.66	21.92
StPaul	15.88	a	1.61	0.50	13.48	19.10
Nanton	15.72	a	1.69	0.39	12.88	18.85
Hanna	15.45	a	3.10	0.40	10.74	24.14
RMH	15.41	a	1.86	0.41	12.04	19.60
RedDeer	15.23	a	1.92	0.41	12.48	19.11
Manning	14.86	ab	1.84	0.41	12.61	19.01
LaCrete	14.24	ab	1.79	0.41	11.17	17.63
MedHat	13.15	b	2.54	0.45	8.77	19.51

Crude Protein in August

Crude protein concentrations declined in August compared to May, with more pronounced regional variation and several significant differences among sites ($p < 0.05$). Manning (15.02% ±2.84 SD) and La Crete (15.01% ± 3.65 SD) had the highest mean CP levels which were slightly elevated compared to May. However, the “min” values show some pastures did decline in CP (shown in Table 7).

Table 7. Mean forage Crude Protein concentrations (% DM) by region in Alberta during August sampling, with standard deviation, standard error, and range.

	CP	Groups	std	se	Min	Max
Manning	15.02	a	2.84	0.55	9.95	21.49
LaCrete	15.01	a	3.65	0.56	7.52	19.80
StPaul	14.48	ab	3.54	0.68	8.75	19.56
Mayerthorpe	14.42	ab	2.60	0.53	9.61	21.36
RMH	12.30	bc	3.01	0.56	7.70	18.48
RedDeer	12.00	bc	3.11	0.56	7.74	20.02
Nanton	11.32	c	2.12	0.54	7.73	15.08
Hanna	11.04	cd	3.03	0.55	6.88	19.09
MedHat	8.74	d	1.52	0.61	6.55	11.38

Medicine Hat had the lowest CP concentration at 8.74% ± 1.52 SD, significantly different from all other sites ($p < 0.05$) with the exception of Hanna, and borderline to the minimum requirement for beef cows in mid-gestation (7–8%).

Variability increased in August compared to May, with standard deviations ranging from 1.52% (Medicine Hat) to 3.65% (La Crete), reflecting higher within-site differences as the growing season progressed. These results suggest that while some northern and central regions maintained adequate protein levels in late summer, supplementation may be warranted in Medicine Hat and potentially in the southern regions such as Hanna and Nanton, depending on specific herd requirements and forage availability.

Crude Protein in October

By October, mean CP concentrations declined across all regions, with notable variability but fewer statistically significant differences among sites. Medicine Hat recorded the lowest CP value at 7.64%, this value falls at the lower threshold of CP required by mid-gestation beef cows (7–8%), suggesting a strong likelihood of inadequate protein availability in that region without supplementation.

Standard deviations were generally higher in October (ranging from 2.10% in RMH to 4.11% in Manning), indicating increased heterogeneity in forage quality as the season progressed. Despite the overall decline in CP, most regions remained above the minimum requirement for mid-gestation cows, though continued monitoring and site-specific management are advised. Medicine Hat stands out as a priority for supplementation.

Table 8. Mean forage Crude Protein concentrations (% DM) by region in Alberta during October sampling, with standard deviation, standard error, and range.

	CP	Groups	std	se	Min	Max
StPaul	12.15	a	3.74	0.73	7.10	19.89
LaCrete	11.05	a	3.16	0.62	5.35	18.06
Manning	10.95	a	4.11	0.60	5.18	18.99
Hanna	10.77	a	3.70	0.58	5.80	23.10
RMH	10.73	a	2.10	0.59	7.22	15.94
RedDeer	10.13	ab	3.13	0.60	4.44	18.46
Mayerthorpe	9.82	ab	2.57	0.57	6.01	16.23
Nanton	9.62	ab	2.54	0.57	5.28	16.49
MedHat	7.64	b	2.25	0.66	4.21	11.75

Crude Protein Discussion

Crude protein concentrations in forage varied both seasonally and across regions, reflecting the complex interplay between plant maturity, species composition, and environmental conditions. For all regions, mean CP concentrations were highest in May, typically exceeding 14%, and declined steadily into August and October. This decline is attributed to increased structural carbohydrate deposition and dilution of protein content as plants mature (Jung & Allen, 1995; Buxton, 1996).

The rate of CP loss between sampling periods varied by region (Table 9). From May to August, regions like Hanna (-4.41%), Nanton (-4.40%), and Medicine Hat (-4.41%) experienced significant declines. Between August and October, the most substantial declines occurred in Mayerthorpe (-4.60%), Manning (-4.07%), and La Crete (-3.97%), suggesting faster degradation of forage quality late in the season. In contrast, Manning and La Crete exhibited minimal CP change from May to August (<1%), indicating potential differences in plant growth stage, regrowth dynamics, or species composition.

These seasonal losses have nutritional implications for beef cattle. According to NRC (2016), mature beef cows in mid-gestation require forage with a minimum CP concentration of approximately 7%. By October, Medicine Hat (7.64% DM) approached this threshold, and though still technically adequate, the mean value suggests that some individual samples fall below requirements. All other regions remained above 9% CP on average, suggesting that supplementation for protein may only be necessary in more arid environments or during years of poor forage growth.

Interannual comparisons revealed significant year effects in only a few regions. In Mayerthorpe, CP concentrations declined significantly in 2024 (11.71%) compared to 2021 and 2023 (13.95% and 14.43%, respectively; $p < 0.05$), and in Medicine Hat, CP dropped from 10.96% in 2023 to 8.73% in 2024. These reductions likely reflect variations in precipitation and heat accumulation, which are known to affect forage nutrient content (Kering et al., 2011). In contrast, no significant differences were observed between years in Rocky Mountain House, Hanna, Manning, St. Paul, or Red Deer, suggesting greater stability of CP in these regions, potentially due to more consistent weather patterns or plant community resilience.

Plant species composition may also explain some of the regional differences observed. Sites with a greater presence of legumes, such as tame pastures in Mayerthorpe or La Crete, likely contribute to higher CP concentrations, as legumes tend to fix atmospheric nitrogen and maintain higher protein content throughout the growing season (Moore et al., 2020). Conversely, in regions dominated by warm-season grasses or drought-tolerant species, such as Medicine Hat, CP concentrations were consistently lower and more susceptible to seasonal decline.

In conclusion, crude protein content in forage exhibited predictable seasonal declines, with regional variability influenced by plant composition and climatic factors. Most regions maintained adequate CP levels for mid-gestation beef cows throughout the growing season, though late-season supplementation may be necessary in more vulnerable regions such as Medicine Hat.

Table 9.Regional differences in CP means from May to August, and August to October

	Sampling Time	diff	lwr	upr	p adj
LaCrete	May-August	0.78	-2.75	1.19	0.61
	August - October	-3.97	-5.96	-1.98	0.00
Manning	May-August	0.16	-2.15	1.83	0.98
	August - October	-4.07	-6.08	-2.07	0.00
StPaul	May-August	-1.40	-1.10	3.91	0.37
	August - October	-2.34	-4.84	0.17	0.07
Mayerthorpe	May-August	-1.58	0.05	3.11	0.04
	August - October	-4.60	-6.13	-3.07	0.00
RedDeer	May-August	-3.24	1.42	5.06	0.00
	August - October	-1.87	-3.71	-0.03	0.04
RMH	May-August	-3.11	1.40	4.82	0.00
	August - October	-1.57	-3.28	0.14	0.08
Hanna	May-August	-4.41	2.08	6.74	0.00
	August - October	-0.27	-2.60	2.06	0.99
Nanton	May-August	-4.40	2.91	5.89	0.00
	August - October	-1.70	-3.19	-0.21	0.02
MedHat	May-August	-4.41	2.86	5.97	0.00
	August - October	-1.10	-2.65	0.45	0.21

Neutral Detergent Fibre

Neutral Detergent Fiber is lowest in May and increases throughout the season. Sampling time ($p = 2.70E-10$) and region ($p < 2e-16$) each have a significant impact on NDF, and the effect of sampling time varies depending on the region ($p = 3.32E-4$), indicating that grass matures at different rates depending on the region.

Neutral Detergent Fibre in May

Neutral Detergent Fiber concentrations in May ranged from 48.17% to 55.20%, with significant regional variation ($p < 0.05$). Med Hat had the highest NDF levels (55.20% ± 3.58 SD), significantly greater than Nanton (48.17% ± 3.54 SD). Most other regions, including La Crete, St. Paul, and Manning, had intermediate values (51–53%) and were not significantly different from one another. The standard deviation across regions ranged from 2.4% to 5.5%, suggesting moderate within-region variability. Standard errors (0.74–0.94%) indicate that while there is some individual variation, mean estimates are relatively stable across sampling sites.

Table 10. Mean forage Neutral Detergent Fibre concentrations (% DM) by region in Alberta during May sampling, with standard deviation, standard error, and range.

	NDF	Groups	std	se	Min	Max
MedHat	55.20	a	3.58	0.85	45.25	60.30
LaCrete	53.09	ab	4.33	0.78	46.75	59.67
StPaul	52.05	abc	2.41	0.94	48.09	55.73
Manning	51.80	abc	4.41	0.76	39.23	57.11
Mayerthorpe	51.47	bc	3.21	0.74	44.05	55.72
Hanna	51.32	bcd	5.52	0.75	36.76	59.97
RedDeer	50.37	bcd	3.40	0.76	43.87	56.81
RMH	49.22	cd	4.09	0.76	43.50	57.53
Nanton	48.17	d	3.54	0.74	42.28	61.00

Neutral Detergent Fibre in August

By August, NDF concentrations increased in all regions, ranging from 53.03% in La Crete to 62.31% in Med Hat. Med Hat remained significantly higher than all other regions ($p < 0.05$), while regions such as Hanna (58.75% ± 5.97 SD) and Red Deer (54.99% ± 3.14 SD) also exhibited elevated fiber concentrations. Most northern and central sites, including Rocky Mountain House, Mayerthorpe, and Manning, clustered in the mid-50% range. Standard deviations were generally higher than in May, reaching up to 5.97% in Hanna, indicating increasing variability in fiber content as the season progressed.

Table 11. Mean forage Neutral Detergent Fibre concentrations (% DM) by region in Alberta during August sampling, with standard deviation, standard error, and range.

	NDF	Groups	std	se	Min	Max
MedHat	62.31	a	3.64	0.92	55.57	70.92
Hanna	58.75	a	5.97	0.83	48.92	72.71
RedDeer	54.99	b	3.14	0.85	49.01	62.65
Nanton	54.39	b	3.46	0.82	48.74	62.09
Manning	53.62	b	4.79	0.83	41.66	60.15
StPaul	53.48	b	4.82	1.02	44.35	62.51
RMH	53.48	b	2.73	0.85	47.01	58.82
Mayerthorpe	53.45	b	3.54	0.80	45.97	59.27
LaCrete	53.03	b	5.63	0.85	40.97	60.53

Neutral Detergent Fibre in October

Neutral Detergent Fibre concentrations peaked in October, reaching as high as 68.39% in Medicine Hat, which remained significantly higher than all other locations ($p < 0.05$) as seen in Table 12. The range in values was broad, with standard deviations up to 7.69% in Manning and standard errors exceeding 1% in several locations, reflecting greater variability in forage maturity and composition at season's end.

Table 12. Mean forage Neutral Detergent Fibre concentrations (% DM) by region in Alberta during October sampling, with standard deviation, standard error, and range.

	NDF	Groups	std	se	Min	Max
MedHat	68.39	a	3.70	1.19	61.67	74.89
Hanna	62.06	b	6.71	1.05	46.03	72.99
StPaul	59.27	bc	6.12	1.31	46.68	66.73
Mayerthorpe	58.37	bc	4.03	1.03	51.59	66.21
LaCrete	58.21	bc	5.28	1.11	42.20	66.43
RedDeer	58.12	bc	5.75	1.09	43.56	70.04
Manning	57.81	bc	7.69	1.09	39.44	71.26
Nanton	57.71	bc	5.62	1.03	50.90	74.14
RMH	56.67	c	3.96	1.07	50.40	64.96

Neutral Detergent Fiber Between Years

There is no significant effect of Year on NDF ($p = 0.82$). In other words, the NDF content does not differ significantly between years.

The interaction between Region and Year is not significant ($p = 0.272$) indicating the effect of Year on NDF does not differ depending on the Region.

Neutral Detergent Fiber Discussion

Neutral Detergent Fibre increased steadily from May through October in all regions, reflecting advancing plant maturity and increasing structural fiber content over the growing season. This seasonal rise in fiber content is a well-documented phenomenon (Jung & Allen, 1995), as plants develop more lignified tissues that reduce digestibility and intake potential for ruminants.

Medicine Hat consistently had the highest NDF concentrations across all months, suggesting a forage base dominated by more mature or coarser species, or possibly limited regrowth due to climatic factors. In contrast, regions like Nanton and Rocky Mountain House maintained lower NDF values, especially early in the season, indicating higher forage quality at those timepoints.

Late-season (October) NDF values not only peaked across all regions but also displayed substantial within-region variability, with standard deviations ranging from 3.70% in Medicine Hat to 7.69% in Manning. Minimum and maximum values were highly divergent illustrating the heterogeneity in forage maturity at this time of year. This variability likely reflects uneven grazing pressure, regrowth potential, and differences in species composition, particularly in mixed pastures. While some pastures offer forage closer to mid-season quality, others exceed 68% NDF, a level that severely limits intake and energy supply (Mertens, 1994). Consequently, regional averages mask potential risk for individual herds. October grazing strategies should account for this uncertainty by incorporating strategic supplementation to maintain animal performance.

Macro Minerals

Calcium

The main effect of region is highly significant (p = 8.66e-16), suggesting that calcium levels vary significantly across regions. This is a strong result, meaning that region has a substantial impact on calcium levels.

Sampling time is statistically significant (p = 0.0142), suggesting that there are significant differences in calcium levels throughout the grazing season. The interaction between sampling time and region is not significant (p = 0.67), meaning the differences in calcium levels due to sampling time are similar across regions.

Calcium in May

Table 13. Mean forage Calcium concentrations (% DM) by region in Alberta during May sampling, with standard deviation, standard error, and range.

	Calcium	Groups	std	se	Min	Max
LaCrete	0.52	a	0.16	0.04	0.22	1.00
Manning	0.50	a	0.46	0.04	0.21	2.06
StPaul	0.43	ab	0.10	0.04	0.28	0.74
Nanton	0.42	ab	0.10	0.04	0.28	0.82
RedDeer	0.42	ab	0.14	0.04	0.29	1.03
Mayerthorpe	0.42	ab	0.09	0.04	0.24	0.67
RMH	0.39	ab	0.09	0.04	0.25	0.63
Hanna	0.34	b	0.05	0.04	0.25	0.47
MedHat	0.33	b	0.09	0.04	0.21	0.58

In May, mean forage Ca concentrations differed significantly among regions ($p < 0.05$) as shown in Table 13. La Crete (0.52% ± 0.16 SD) and Manning (0.50% ± 0.46 SD) had the highest Ca levels and were statistically greater than Hanna (0.34% ± 0.05 SD) and Medicine Hat (0.33% ± 0.05 SD). St. Paul, Nanton, Red Deer, Mayerthorpe, and Rocky Mountain House had intermediate concentrations (0.39–0.43% DM) and did not differ significantly from either group. Calcium values ranged from 0.21% to 2.06% DM across all regions, with the highest individual variability observed in Manning.

Calcium in August

La Crete had the highest mean Ca concentration (0.64% ± 0.41 SD), which was significantly greater than values observed in Hanna (0.33% ± 0.09 SD) and Medicine Hat (0.31% ± 0.11 SD), as shown in Table 14. Manning (0.54% ± 0.51 SD) was also elevated but not statistically different from most other regions. Calcium values across all regions ranged from 0.13% to 2.36% DM, with the greatest variability again observed in Manning.

Table 14. Mean forage Calcium concentrations (% DM) by region in Alberta during August sampling, with standard deviation, standard error, and range.

	Calcium	Groups	std	se	Min	Max
LaCrete	0.64	a	0.41	0.05	0.25	1.81
Manning	0.54	ab	0.51	0.05	0.27	2.36
StPaul	0.51	abc	0.16	0.06	0.30	0.88
Nanton	0.51	abc	0.15	0.05	0.32	0.97
RMH	0.49	abc	0.10	0.05	0.33	0.70
RedDeer	0.45	abc	0.10	0.05	0.23	0.73
Mayerthorpe	0.43	bc	0.08	0.05	0.33	0.65
Hanna	0.33	c	0.09	0.05	0.13	0.46
MedHat	0.31	c	0.11	0.05	0.16	0.52

Calcium in October

Table 15. Mean forage Calcium concentrations (% DM) by region in Alberta during October sampling, with standard deviation, standard error, and range.

	Calcium	Groups	std	se	Min	Max
Manning	0.71	a	0.67	0.05	0.23	3.45
LaCrete	0.68	a	0.24	0.05	0.35	1.39
RedDeer	0.60	ab	0.13	0.05	0.36	0.85
Mayerthorpe	0.59	ab	0.16	0.05	0.36	0.93
StPaul	0.58	abc	0.19	0.06	0.28	0.93
RMH	0.57	abc	0.14	0.05	0.35	0.80
Nanton	0.53	abc	0.17	0.05	0.26	1.00
Hanna	0.37	bc	0.08	0.05	0.21	0.58
MedHat	0.31	c	0.10	0.06	0.16	0.48

Calcium continues to increase in forage from August to October in all areas except for Medicine Hat, which shows no change in the mean Ca content. The highest Ca concentrations were found in Manning (0.71% ± 0.67 SD) and La Crete (0.68% ± 0.24 SD), which were significantly greater than values in Medicine Hat (0.31% ± 0.10 SD).

Calcium Between Years

Year does not have a significant effect on Calcium content across the regions ($p > 0.05$), meaning the levels of Ca are similar across the 3 years sampled. Interaction between Region and Year is not significant ($p = 0.113$), meaning the effect of Year on Ca content does not vary by Region.

Calcium Discussion

Forage Ca concentrations in this study exhibited both seasonal and regional variation, reflecting underlying differences in plant maturity, species composition, and environmental conditions. Across all sampling periods, Ca levels were consistently higher in northern regions such as La Crete and Manning, and lower in southeastern regions such as Hanna and Medicine Hat. Seasonally, Ca concentrations were lowest in May and increased into August and October, a pattern that diverges from previous literature reporting relatively stable Ca concentrations as plants mature (Schlegel et al., 2016). Calcium is generally considered immobile in plant tissues and is predominantly located in the cell wall (Whitehead et al., 1985), which is often interpreted to mean that its concentration remains consistent as the plant grows.

The increase in Ca later in the growing season may be influenced by changes in plant community structure over time. Regions with higher proportions of tame pasture, such as La Crete, Mayerthorpe, and Manning, are more likely to include legumes like alfalfa or clover, which contain significantly higher calcium concentrations than grasses (McDowell, 2003). In contrast, native pastures, more typical of southern regions such as Hanna and Nanton, are often dominated by grass species with lower calcium content (Schlegel et al., 2016). This is supported by the observed pattern of lower Ca concentrations in areas with primarily native or mixed pastures (Table 1).

High within-region variability, particularly in Manning, where Ca concentrations ranged from 0.23% to 3.45% DM, further suggests that local soil conditions and plant species composition may influence Ca uptake and accumulation.

From a livestock nutrition standpoint, adequate Ca intake is critical for bone development, milk production, and reproductive efficiency (NRC, 2016). While many regions in this study exceeded the Ca requirements for beef cattle (typically 0.18–0.31% DM depending on physiological stage), regions with lower forage Ca may require supplementation to prevent subclinical deficiencies, particularly in early-season samples or in native-dominated pastures.

Phosphorus

Phosphorus concentrations were highest in the May sampling period and declined throughout the grazing season. Phosphorus levels were significantly influenced by both sampling time ($p < 2e-16$) and region ($p < 2e-16$). A significant interaction between sampling time and region ($p = 0.048$) suggests that the rate and extent of phosphorus decline varies geographically.

Phosphorus in May

Early-season phosphorus concentrations varied significantly by region ($p < 0.05$), with the highest means in Manning (0.30% ± 0.07 SD) and Mayerthorpe (0.30% ± 0.08 SD), and the lowest in Medicine Hat (0.19% ± 0.06 SD; Table 16). All regions exceeded the 0.14% DM requirement for mature cows in mid-gestation (NRC, 2016), suggesting adequate P availability across Alberta pastures in May.

Table 16. Mean forage Phosphorus concentrations (% DM) by region in Alberta during May sampling, with standard deviation, standard error, and range.

	Phosphorus	Groups	std	se	Min	Max
Manning	0.30	a	0.07	0.01	0.21	0.48
Mayerthorpe	0.30	a	0.08	0.01	0.12	0.46
RMH	0.29	ab	0.09	0.01	0.16	0.44
LaCrete	0.29	ab	0.11	0.02	0.14	0.51
StPaul	0.27	abc	0.06	0.02	0.14	0.38
RedDeer	0.26	abc	0.06	0.01	0.14	0.36
Nanton	0.25	abc	0.06	0.01	0.13	0.38
Hanna	0.23	bc	0.09	0.01	0.14	0.46
MedHat	0.19	c	0.06	0.02	0.08	0.28

Phosphorus in August

Phosphorus declined from May to August in all regions. Manning (0.26% ± 0.10 SD), La Crete (0.24% ± 0.10 SD), and Mayerthorpe (0.23% ± 0.07 SD) maintained the highest concentrations, while Medicine Hat (0.11% ± 0.05 SD), Nanton (0.14% ± 0.04 SD), and Hanna (0.14% ± 0.04 SD) fell at or below the 0.14% threshold.

Table 17. Mean forage Phosphorus concentrations (% DM) by region in Alberta during August sampling, with standard deviation, standard error, and range.

	Phosphorus	Groups	std	se	Min	Max
Manning	0.26	a	0.10	0.01	0.16	0.47
LaCrete	0.24	ab	0.10	0.01	0.09	0.53
Mayerthorpe	0.23	ab	0.07	0.01	0.13	0.38
StPaul	0.21	abc	0.07	0.02	0.11	0.37
RMH	0.19	bcd	0.07	0.01	0.09	0.38
RedDeer	0.17	cde	0.05	0.01	0.06	0.30
Hanna	0.14	de	0.04	0.01	0.07	0.23
Nanton	0.14	de	0.04	0.01	0.06	0.21
MedHat	0.11	e	0.05	0.01	0.04	0.22

Phosphorus in October

By October, phosphorus concentrations fell further. Only St. Paul (0.16%), Rocky Mountain House (0.15%), and Mayerthorpe (0.14%) maintained means at or slightly above the requirement. All others fell below 0.14%, with Medicine Hat (0.07% ± 0.02 SD), Hanna (0.10% ± 0.05 SD), and Nanton (0.10% ± 0.04 SD) showing the lowest values. The minimum values show that some pastures in each area fellow below the requirement threshold. This data strongly indicates that phosphorus supplementation would be necessary for all regions during fall grazing to maintain animal health and performance.

Table 18. Mean forage Phosphorus concentrations (% DM) by region in Alberta during October sampling, with standard deviation, standard error, and range.

	Phosphorus	Groups	std	se	Min	Max
StPaul	0.16	a	0.05	0.01	0.08	0.31
RMH	0.15	a	0.05	0.01	0.06	0.27
Mayerthorpe	0.14	a	0.06	0.01	0.06	0.27
Manning	0.14	ab	0.04	0.01	0.09	0.23
LaCrete	0.14	abc	0.06	0.01	0.04	0.35
RedDeer	0.13	abc	0.06	0.01	0.04	0.28
Hanna	0.10	bcd	0.05	0.01	0.05	0.28
Nanton	0.10	cd	0.04	0.01	0.04	0.17
MedHat	0.07	d	0.02	0.01	0.04	0.10

Phosphorus Between Years

There is no significant difference in Phosphorus content between the years ($p = 0.47$). However, the interaction between Region and Year is significant ($p = 0.0184$), indicating that the effect of region on phosphorus content depends on the year, and the difference between regions may vary across years.

Phosphorus Discussion

Phosphorus concentrations exhibited a clear seasonal decline across all regions, a trend consistent with plant maturation and nutrient translocation as the growing season progresses (McDowell, 2003; NRC, 2016). In May, all regions exceeded the 0.14% DM phosphorus requirement for mature beef cows in mid-gestation (NRC, 2016) However, by August several regions, particularly Medicine Hat, Hanna, and Nanton, had phosphorus concentrations near or below the requirement of 0.14% DM indicating an emerging risk of phosphorus deficiency as summer advanced.

October, all regions exhibited mean phosphorus values that were either at or below this requirement, indicating a widespread and predictable need for phosphorus supplementation during fall grazing. This seasonal trend is expected, as phosphorus is a mobile nutrient within plants and is readily translocated from leaves to reproductive tissues or roots during maturation, leading to lower concentrations in mature forage (Schlegel et al., 2016; McDowell, 2003).

The sharpest declines in phosphorus were observed in Nanton (–0.11% from May to August) and Manning (–0.12% from August to October) as seen in Table 19, demonstrating that regional forage characteristics such as plant species, soil fertility, and climatic conditions strongly influence phosphorus retention (Jones & Tracy, 2015).

Differences among regions may also reflect underlying variation in soil phosphorus levels, precipitation, and plant species composition. Regions with higher proportions of tame pasture, such as Mayerthorpe and Manning, showed relatively higher phosphorus concentrations early in the season, potentially due to the presence of legumes, which are typically richer in P compared to grasses (NRC, 2016). However, even these regions experienced significant reductions by October.

Given the essential role of phosphorus in energy metabolism, reproductive performance, and skeletal integrity (McDowell, 2003), inadequate P intake can impair both animal health and productivity. The data suggest that while early-season forage may generally meet requirements, strategic phosphorus supplementation becomes necessary in most regions by mid to late season to support the nutritional demands of gestating beef cattle.

Table 19. Rate of Phosphorus loss (% DM) in pasture forage throughout the grazing period.

Region	Comparison	Diff	Lwr	Upr	P_adj
Nanton	May-August	-0.11	0.08	0.14	0.00
RMH	May-August	-0.10	0.05	0.15	0.00
RedDeer	May-August	-0.09	0.06	0.13	0.00
Hanna	May-August	-0.09	0.04	0.14	0.00
MedHat	May-August	-0.08	0.05	0.11	0.00
Mayerthorpe	May-August	-0.07	0.03	0.12	0.00
StPaul	May-August	-0.06	0.01	0.11	0.02
Manning	October-August	-0.12	-0.16	-0.07	0.00
LaCrete	October-August	-0.10	-0.17	-0.04	0.00
Mayerthorpe	October-August	-0.09	-0.13	-0.04	0.00
RedDeer	October-August	-0.04	-0.08	0.00	0.03
MedHat	October-August	-0.04	-0.07	-0.01	0.01
Nanton	October-August	-0.04	-0.07	-0.01	0.02

Magnesium

Our data shows region had a significant effect on Mg content ($p < 2e-16$). Sampling time did not have a significant effect ($p = 0.697$) and there was no significant interaction between sampling time and region ($p = 0.854$), suggesting the effect of region on Mg content is consistent across different sampling times.

Regional effects of Magnesium

Table 20. Mean Magnesium concentrations (% DM) in forage samples across nine regions in Alberta.

	Magnesium	Groups	std	se	Min	Max
Manning	0.21	a	0.10	0.01	0.12	0.69
LaCrete	0.18	b	0.05	0.01	0.09	0.37
StPaul	0.16	bc	0.04	0.01	0.10	0.30
RMH	0.16	bcd	0.03	0.01	0.09	0.24
Mayerthorpe	0.14	cde	0.03	0.01	0.07	0.26
RedDeer	0.14	cde	0.03	0.01	0.06	0.25
Nanton	0.14	de	0.05	0.01	0.06	0.38
Hanna	0.12	ef	0.03	0.01	0.05	0.22
MedHat	0.11	f	0.03	0.01	0.05	0.20

Across the study sites, forage Mg concentrations exhibited significant regional variation (Table 20). Manning had the highest mean Mg concentration (0.21% ± 0.10 SD), significantly greater than all other regions ($p < 0.05$). La Crete (0.18% ± 0.05 SD) and St. Paul (0.16% ± 0.04 SD) also showed relatively elevated Mg levels, while the lowest concentrations were observed in Hanna (0.12% ± 0.03 SD) and Medicine Hat (0.11% ± 0.03 SD). The standard deviation was highest in Manning (0.10%), suggesting considerable variability in forage Mg within this region. In contrast, regions such as Rocky Mountain House and Red Deer displayed more consistent Mg concentrations, indicated by lower standard deviations (0.03%).

Magnesium Between Years

No difference in the Mg content between years ($p = 0.38$) meaning that weather did not significantly impact the Mg content of pasture grass within each region. There was a significant interaction between region and year ($p = 0.036$) indicating that regional Mg content depends on weather, and the difference between regions may vary across years.

Magnesium Discussion

The National Research Council (NRC, 2016) recommends a minimum dietary Mg concentration of 0.12% of dry matter for mature beef cows in mid-gestation. On average, most regions met or exceeded this threshold. However, the forage in Medicine Hat and Hanna approached or fell below this requirement, increasing the risk of subclinical Mg deficiency or conditions such as grass tetany, particularly under stress or when potassium intake is high.

A key factor influencing Mg content is plant species composition. Legumes are known to contain higher Mg concentrations than grasses (Rayburn & Matlick, 2012), and this likely contributed to the elevated Mg levels observed in northern regions such as Manning and La Crete. However, Medicine Hat still showed the lowest Mg concentrations despite having 73% of its pastures classified as tame, including legumes. This suggests that other environmental factors, particularly soil nutrient status and drought stress, are also influential.

According to Rayburn & Matlick (2012), P is required to facilitate Mg absorption. In our study, northern regions (Manning, La Crete) maintained higher forage P concentrations compared to southern regions (Hanna, Nanton, and Medicine Hat). This geographic pattern likely contributes to the higher Mg concentrations observed in the north relative to lower Mg values in southern regions. When soil P availability is limited, as in drier southern Alberta, Mg uptake by plants may be suppressed even if Mg is present in the soil.

Potassium

Potassium is highest in the May sampling and gradually decreases through August and October as the grass matures. Sampling time ($p < e\text{-}16$) and region ($p < e\text{-}16$) are significant predictors of potassium levels. The interaction between sampling time and region is not significant ($p = 0.7$), meaning the influence of sampling time on potassium levels is consistent across regions.

Potassium in May

Potassium concentrations in forage varied by region, ranging from 1.70% to 2.74% DM (Table 21). The highest mean potassium concentration was observed in Manning (2.74% ± 0.44 SD), followed closely by Mayerthorpe (2.72% ± 0.51 SD) and La Crete (2.56% ± 0.54 SD). Potassium concentrations were lower in the southern and southeastern sites, Medicine Hat having the lowest mean potassium concentration overall. Despite this variation, all locations exceeded the minimum dietary potassium requirement for beef cattle (0.6–0.7%), suggesting that forage potassium was adequate across Alberta during the spring sampling period.

Table 21. Mean forage Potassium concentrations (% DM) by region in Alberta during May sampling, with standard deviation, standard error, and range.

	Potassium	Groups	std	se	Min	Max
Manning	2.74	a	0.44	0.09	2.02	3.51
Mayerthorpe	2.72	a	0.51	0.09	1.88	3.74
LaCrete	2.56	a	0.54	0.09	1.47	3.5
StPaul	2.56	ab	0.33	0.11	1.87	3.09
RedDeer	2.51	ab	0.29	0.09	1.76	3.07
RMH	2.47	ab	0.45	0.09	1.63	3.4
Nanton	2.12	bc	0.34	0.09	1.26	2.85
Hanna	1.83	cd	0.67	0.09	0.67	3.68
MedHat	1.70	d	0.45	0.10	0.6	2.57

Potassium in August

Potassium concentrations in forage samples collected in August continued to show regional variation across Alberta, with values ranging from 1.01% to 2.01% on a dry matter basis (Table 22). The highest mean concentration was recorded in Manning (2.01% ± 0.96 SD), with La Crete and St. Paul closely matching at 1.97%.

Lower potassium concentrations were observed in the southern sites, continuing the trend noted in May. These results indicate that by August, potassium levels in forages had declined across all sites compared to May, with southern Alberta regions showing greater reductions.

Although all locations except Medicine Hat remained above the minimum dietary potassium requirement for beef cattle (0.6–0.7%), the narrowing margin in Hanna and Nanton highlights a potential risk for deficiency, particularly during periods of physiological stress or high production demand.

Table 22. Mean forage Potassium concentrations (% DM) by region in Alberta during August sampling, with standard deviation, standard error, and range.

	Potassium	Groups	std	se	Min	Max
Manning	2.01	a	0.96	0.11	1.19	4.76
LaCrete	1.97	a	0.64	0.12	1.12	3.78
StPaul	1.97	a	0.69	0.14	0.80	3.40
RMH	1.75	ab	0.55	0.12	0.91	3.28
RedDeer	1.74	ab	0.55	0.12	0.72	3.10
Mayerthorpe	1.73	ab	0.47	0.11	1.05	2.89
Nanton	1.38	bc	0.30	0.11	0.88	1.82
Hanna	1.18	c	0.50	0.11	0.48	2.29
MedHat	1.01	c	0.42	0.13	0.36	1.77

Potassium in October

By October, potassium concentrations in forage samples had declined further across all locations in Alberta, ranging from 0.43% to 1.45% on a dry matter basis (Table 23). The highest potassium level was observed in St. Paul followed by Manning, Mayerthorpe, and La Crete.

Table 23. Mean forage Potassium concentrations (% DM) by region in Alberta during October sampling, with standard deviation, standard error, and range.

	Potassium	Groups	std	se	Min	Max
StPaul	1.45	a	0.47	0.12	0.85	2.43
Manning	1.38	ab	0.73	0.10	0.46	2.61
Mayerthorpe	1.23	abc	0.58	0.09	0.46	2.39
LaCrete	1.15	abc	0.57	0.10	0.32	2.65
RMH	1.03	abcd	0.38	0.10	0.45	2.00
RedDeer	0.96	bcd	0.45	0.10	0.49	2.23
Nanton	0.87	cde	0.49	0.09	0.41	2.63
Hanna	0.68	de	0.50	0.10	0.29	2.28
MedHat	0.43	e	0.15	0.11	0.24	0.82

More pronounced reductions in potassium were recorded in the central and southern regions. Medicine Hat (0.43% ± 0.15 SD) had the lowest recorded potassium concentration.

By October, potassium levels had fallen below or approached the minimum dietary requirement (0.6–0.7%), in multiple locations, particularly in southern Alberta. This highlights a clear need for potassium supplementation during fall grazing in regions such as Medicine Hat, Hanna, and Nanton to prevent potential deficiencies in beef cattle diets.

Potassium Between Years

Year, and the interaction between region and year did not have a significant effect on potassium levels ($p > 0.05$) meaning each region is equally impacted by weather and other variables that may impact potassium content of pasture forage.

Potassium Discussion

The observed variation in forage potassium concentrations across Alberta is influenced by seasonal changes, but also by the composition of native and tame grasses in each region, and environmental factors such as soil type, soil pH, and local climate conditions. Regions dominated by tame grasses or mixed stands, such as La Crete (100% tame) and Mayerthorpe (90% tame), generally exhibited higher potassium concentrations in their forages, especially in the spring and summer months. This pattern aligns with previous research showing that tame grass species, often selected for higher nutritional quality, tend to accumulate more potassium compared to native grass species (McDowell, 2003).

Conversely, regions with a higher proportion of native grasses, such as Nanton (78% native) and Hanna (67% native) consistently exhibited lower potassium concentrations, particularly in the fall. Native grasses may have inherently lower potassium uptake or retention capacities, potentially due to adaptation to less fertile soils (Bisangwa et al., 2025). Additionally, soil characteristics likely contribute significantly to the regional potassium variability. Southern Alberta sites like Medicine Hat and Hanna, which showed the lowest potassium levels, are characterized by coarser-textured, well-drained soils with lower cation exchange capacity and often higher pH values (alkaline conditions), which can limit potassium availability to plants (Morgan and Connolly, 2013).

Seasonal weather patterns also affect potassium dynamics. Potassium uptake is generally higher during active growth periods in spring and early summer when soil moisture and temperatures favor nutrient absorption. Declines in potassium levels by October correspond with reduced plant growth and dormancy onset, reducing potassium uptake and translocation to above-ground biomass. Dry conditions, common in southern Alberta during late summer and fall, can exacerbate potassium depletion in forages (NRC, 2016).

Sulphur

Our results show that region ($p < 2e-16$) and sampling time ($p = 8.31e-05$) both have a significant effect on sulphur levels. The interaction between sampling time and region is not significant ($p = 0.693$) implying that the effect of sampling time does not differ greatly between regions.

Sulphur in May

Table 24. Mean forage Sulphur concentrations (% DM) by region in Alberta during May sampling, with standard deviation, standard error, and range.

	Sulphur	Groups	std	se	Min	Max
LaCrete	0.23	a	0.06	0.01	0.12	0.36
Manning	0.23	ab	0.03	0.01	0.16	0.29
Mayerthorpe	0.22	ab	0.06	0.01	0.12	0.34
Nanton	0.19	bc	0.03	0.01	0.14	0.25
StPaul	0.19	bc	0.04	0.01	0.13	0.25
RedDeer	0.18	cd	0.03	0.01	0.12	0.28
RMH	0.17	cd	0.06	0.01	0.10	0.34
Hanna	0.17	cd	0.05	0.01	0.11	0.29
MedHat	0.14	d	0.03	0.01	0.06	0.21

In May, forage sulphur concentrations varied across regions, with values ranging from 0.14% to 0.23% (Table 24). The highest mean sulphur levels were recorded in La Crete (0.23% ± 0.06 SD) and Manning (0.23% ± 0.03 SD). Mayerthorpe also showed elevated sulphur (0.22% ± 0.06 SD), while southern regions such as Medicine Hat (0.14% ± 0.03 SD) and Hanna (0.17% ± 0.05 SD) had the lowest concentrations.

Sulphur in August

Table 25. Mean forage Sulphur concentrations (% DM) by region in Alberta during August sampling, with standard deviation, standard error, and range.

	Sulphur	Groups	std	se	Min	Max
LaCrete	0.21	a	0.07	0.01	0.08	0.32
Manning	0.21	a	0.06	0.01	0.12	0.35
Mayerthorpe	0.18	ab	0.04	0.01	0.11	0.27
StPaul	0.16	ab	0.06	0.01	0.08	0.32
Nanton	0.15	b	0.05	0.01	0.09	0.28
RMH	0.15	bc	0.05	0.01	0.06	0.24
RedDeer	0.14	bc	0.03	0.01	0.06	0.19
Hanna	0.14	bc	0.05	0.01	0.07	0.30
MedHat	0.10	c	0.04	0.01	0.06	0.21

In August, sulphur concentrations in forage continued to show regional variation, with means ranging from 0.10% to 0.21%. La Crete and Manning maintained the highest levels (0.21%), while Medicine Hat again recorded the lowest sulphur concentration (0.10% ± 0.04 SD). Intermediate values were observed in Mayerthorpe (0.18% ± 0.04 SD), St. Paul (0.16% ± 0.06 SD), and Nanton (0.15% ± 0.05 SD). Several central and southern locations, including Red Deer, Rocky Mountain House, and Hanna, showed moderate to low sulphur levels (0.14–0.15%). While most sites remained near or above the minimum requirement for cattle (0.15%; NRC, 2016), seasonal decline was evident.

Sulphur in October

By October, forage S concentrations declined further across most locations, ranging from 0.08% to 0.16%. Manning (0.16% ± 0.07 SD) and La Crete (0.16% ± 0.07 SD) remained at the upper end. Mayerthorpe, St. Paul, and Nanton followed closely at 0.15%. In contrast, Medicine Hat recorded the lowest mean S concentration at 0.08% ± 0.02 SD. Central and southern regions, including Red Deer, Rocky Mountain House, and Hanna, exhibited lower concentrations (0.11–0.12%), indicating a continued seasonal decline. Several locations approached or fell below the recommended minimum dietary level for beef cattle, suggesting a potential need for late-season supplementation.

Table 26. Mean forage Sulphur concentrations (% DM) by region in Alberta during October sampling, with standard deviation, standard error, and range.

	Sulphur	Groups	std	se	Min	Max
Manning	0.16	a	0.07	0.01	0.08	0.42
LaCrete	0.16	ab	0.07	0.01	0.06	0.35
Mayerthorpe	0.15	ab	0.06	0.01	0.00	0.33
StPaul	0.15	ab	0.05	0.01	0.08	0.26
Nanton	0.15	ab	0.06	0.01	0.06	0.34
RedDeer	0.12	abc	0.04	0.01	0.06	0.22
RMH	0.11	bc	0.05	0.01	0.05	0.20
Hanna	0.11	bc	0.04	0.01	0.07	0.20
MedHat	0.08	c	0.02	0.01	0.04	0.10

Sulphur Between Years

Year did not show a significant effect on S levels ($p = 0.0691$), meaning that forage S content does not differ greatly from year to year. When looking at the interaction between region and year, the p-value was significant ($p = 0.044$) meaning the relationship between region and S levels may not be consistent across years. The probability was close to the threshold; therefore, further analysis of the interaction would be necessary to understand how these factors jointly influence S levels.

Sulphur Discussion

Forage sulphur concentrations exhibited clear seasonal and regional patterns, with levels generally declining from spring through fall. Beef cattle require a minimum of approximately 0.15% sulphur on a dry matter basis, with maximum tolerable levels near 0.4% to avoid toxicity (NRC, 2016). In this study, early-season forage sulphur concentrations in northern regions such as La Crete and Manning were among the highest, averaging around 0.23%, and remained relatively elevated through October (~0.16%). In contrast, southern and central regions such as Medicine Hat consistently exhibited lower sulphur concentrations, dropping to as low as 0.08% by fall.

The observed persistence of higher sulphur content in northern sites can be attributed in part to forage species composition, where alfalfa and other legumes dominate tame pastures. Legumes are well documented to contain higher sulphur concentrations compared to native or tame grasses, as sulphur is essential for the synthesis of sulphur-containing amino acids (methionine and cysteine) which are abundant in legume proteins (McDowell, 2003; Ren, 2022). The prevalence of alfalfa in the northern pastures, likely supported by favorable moisture conditions, may contribute to both the elevated and more stable sulphur levels observed in these regions. Additionally, moisture availability in the north may prolong the active growth phase or induce regrowth in late summer and early fall, maintaining higher nutrient concentrations including sulphur, whereas southern regions experience earlier senescence under drier conditions leading to more pronounced nutrient declines. This seasonal decline in sulphur corresponds with reduced forage protein content and increased structural carbohydrate accumulation as plants mature (Suttle, 2010).

While mean sulphur levels remained mostly within safe nutritional ranges, the presence of individual forage samples with sulphur concentrations approaching the upper limit (~0.4%) warrants caution. Supplementation strategies, including the use of sulphur-containing feed additives such as garlic-based fly control products, must be carefully managed to avoid exceeding tolerable sulphur thresholds, which can lead to adverse health effects like polioencephalomalacia (Gould, 2000).

Environmental contamination from oil and gas activities may also influence regional forage sulphur levels. In Alberta, emissions of sulphur compounds such as hydrogen sulfide (H_2S) and sulfur dioxide (SO_2) from petroleum extraction are significant sources of atmospheric sulphur deposition (You et al., 2024). Such emissions can increase sulphur inputs to soil and vegetation, potentially elevating forage sulphur concentrations in proximity to oil and gas operations (Ren et al., 2022). This factor may contribute to the observed variability and relatively elevated sulphur levels in central Alberta regions such as Red Deer and Rocky Mountain House, where oil and gas activities are prominent. However, chronic exposure to elevated sulphur emissions can also negatively affect soil microbial communities and plant health, possibly leading to inconsistent forage quality (Liu et al., 2017; You et al., 2024).

Trace Minerals

Copper

Copper content in forage generally declined from spring (May) to fall (October) across Alberta, with northern regions consistently showing higher copper concentrations than southern regions. Variability in copper concentrations tended to increase in summer and fall months, as shown by increasing standard deviations. These seasonal trends may relate to changes in forage species composition, plant growth stages, and soil-copper bioavailability.

Our data shows region (p = 2e-16) and sampling time (p = 2e-16) are highly significant, indicating substantial differences in copper levels across the various regions and throughout the grazing season. The interaction between sampling time and region is also highly significant (p = 3.79e-07), meaning the effect of sampling time on copper varies depending on the region.

Copper in May

Copper concentrations in May ranged from a minimum of 2.34 ppm in Medicine Hat to a maximum of 10.47 ppm in Mayerthorpe. The highest mean copper content was observed at Manning (7.24 ppm ± 1.15 SD), followed by St. Paul (6.74 ppm ± 1.09 SD) and Mayerthorpe (6.41 ppm ± 1.28 SD). The lowest mean copper levels were found in Medicine Hat (4.57 ppm ± 1.07 SD) and Hanna (4.65 ppm ± 1.03 SD). Standard errors ranged from 0.20 to 0.34, indicating reasonable precision in the estimates. There was a noticeable geographic trend with northern regions tending toward higher copper concentrations compared to southern sites.

Table 27. Mean forage Copper concentrations (mg/kg DM) by region in Alberta during May sampling, with standard deviation, standard error, and range.

	Copper	Group	SD	SE	Min	Max
Manning	7.24	a	1.15	0.22	5.69	9.52
StPaul	6.74	ab	1.09	0.26	4.37	8.67
Mayerthorpe	6.41	ab	1.28	0.24	4.22	10.47
LaCrete	6.40	ab	1.75	0.34	2.61	9.06
RMH	6.22	ab	1.23	0.24	3.67	9.44
Nanton	6.12	b	0.94	0.17	3.67	7.84
RedDeer	6.06	b	1.04	0.20	3.58	7.86
Hanna	4.65	c	1.03	0.20	2.88	6.29
MedHat	4.57	c	1.07	0.23	2.34	7.42

Copper in August

Table 28. Mean forage Copper concentrations (mg/kg DM) by region in Alberta during August sampling, with standard deviation, standard error, and range.

	Copper	Group	SD	SE	Min	Max
Manning	6.32	a	1.83	0.37	4.06	10.52
LaCrete	6.19	ab	1.87	0.37	3.20	9.36
StPaul	5.90	ab	1.81	0.43	3.46	9.09
Mayerthorpe	5.26	abc	1.20	0.22	3.63	9.42
RMH	5.04	bcd	1.58	0.30	2.83	8.96
RedDeer	4.38	cd	1.21	0.24	2.06	6.89
Nanton	4.18	cde	0.71	0.13	2.84	5.60
Hanna	3.94	de	1.34	0.25	2.17	7.52
MedHat	2.94	e	0.82	0.17	1.86	4.92

Copper levels generally decreased compared to May. Manning maintained the highest mean copper concentration at 6.32 ppm (± 1.83 SD), though variability was greater (SE = 0.37). Other northern locations such as La Crete (6.19 ppm ± 1.87 SD) and St. Paul (5.90 ppm ± 1.81 SD) also exhibited relatively elevated copper levels. Southern regions such as Medicine Hat (2.94 ppm ± 0.82 SD) and Hanna (3.94 ppm ± 1.34 SD) showed the lowest concentrations. The spread of values increased as indicated by higher standard deviations, suggesting more heterogeneity in forage copper levels during late summer.

Copper in October

Table 29. Mean forage Copper concentrations (mg/kg DM) by region in Alberta during October sampling, with standard deviation, standard error, and range.

	Copper	Group	SD	SE	Min	Max
StPaul	6.38	a	2.22	0.62	3.83	10.37
Manning	5.42	ab	2.13	0.43	2.65	10.61
LaCrete	4.94	ab	1.64	0.33	2.15	8.78
Mayerthorpe	4.71	bc	1.77	0.40	2.51	7.94
RMH	4.36	bcd	1.43	0.28	2.32	7.84
RedDeer	3.65	cde	0.99	0.19	2.42	5.88
Nanton	3.33	de	1.18	0.22	2.02	7.07
Hanna	2.95	e	0.88	0.17	1.89	5.44
MedHat	2.86	e	0.72	0.15	1.88	4.33

Copper concentrations further declined by October, with St. Paul recording the highest mean copper concentration (6.38 ppm ± 2.22 SD), followed by Manning (5.42 ppm ± 2.13 SD). Southern locations again had the lowest mean copper contents, notably Medicine Hat (2.86 ppm ± 0.72

SD) and Hanna (2.95 ppm ± 0.88 SD). Standard errors remained generally consistent with August. Copper content showed a clear seasonal decrease, consistent across most sites.

Copper Between Years

Statistical analysis indicates that both Year ($p < 0.001$) and the interaction between Region and Year ($p < 0.016$) have significant effects on copper concentrations. These results suggest that changes in copper levels over time are not consistent across all regions.

Significant year-to-year variations in copper concentrations were observed in Manning, St. Paul, and Mayerthorpe. Whereas La Crete, Red Deer, Rocky Mountain House, Hanna, Nanton, and Medicine Hat did not exhibit statistically significant changes (Table 30).

Copper Discussion

The NRC (2016) specifies that beef cattle require approximately 10 mg/kg copper in their diet to support optimal health and production. The forage copper concentrations measured across Alberta in this study consistently fell below this threshold, particularly in southern regions such as Medicine Hat and Hanna. This aligns with previous findings that copper availability in forage is often limited by soil characteristics such as pH, organic matter content, and soil copper pools (Penney, 2002). Lower copper levels in southern Alberta may be exacerbated by alkaline soils that reduce copper bioavailability (Jones & Tracy, 2015).

Table 30. *Post-hoc Tukey's test showing significant and numerical differences in copper content of pasture grass in years 2021,2023, and 2024.*

Post-hoc Tukey's test for Manning :		
Year	Copper	groups
2021	5.56	a
2023	6.40	ab
2024	7.27	b
Post-hoc Tukey's test for StPaul :		
Year	Copper	groups
2023	5.74	a
2024	7.07	b
Post-hoc Tukey's test for Mayerthorpe :		
Year	Copper	groups
2021	4.78	a
2023	6.08	b
2024	5.95	b
No significant difference in years for LaCrete		
No significant difference in years for RedDeer		
No significant difference in years for RMH		
No significant difference in years for Hanna		
No significant difference in years for Nanton		

Seasonal decreases in copper concentration from May to October likely result from dilution effects as plant biomass increases and copper uptake decreases in mature forage (McDowell, 1996). Furthermore, copper absorption by cattle is estimated to be between 1–10% of the copper available in the forage (Spears, 2003), indicating that even forage copper concentrations near the requirement may not meet animal needs without supplementation. This seasonal trend and low bioavailability highlight the importance of considering forage growth stage and absorption efficiency when designing supplementation strategies.

Copper deficiency in beef cattle is linked to impaired immune function, reproduction, and growth (Ward et al., 1997). Given the suboptimal copper levels found in forage, supplementation programs are recommended to mitigate deficiency risks.

Antagonism greatly impacts copper absorption in ruminants. A well-known interaction occurs between Cu, Mo, and S, where Mo and S form thiomolybdates in the rumen that tightly bind Cu, making it unavailable for absorption (Allen & Gawthorne, 1987). Copper absorption is already low, estimated to be between 1–10% of the Cu available in the plant (Spears, 2003), so factors further limiting bioavailability can exacerbate deficiency.

The risk of Cu antagonism through thiomolybdates depends largely on the concentrations of Mo and S in the diet. Molybdenum levels greater than 3 mg/kg dry matter are considered elevated and can significantly reduce copper bioavailability, especially when dietary sulfur exceeds 0.2% DM (McDowell, 2003). When ruminal sulfur concentrations are low, molybdenum may have little effect on copper absorption (Ward et al., 1997), but areas with elevated sulfur and molybdenum pose a higher risk (Gooneratne et al., 1989).

Table 31. Regional Risk of Secondary Copper Deficiency through Thiomolybdate Antagonism

Region	Mo (mg/kg)	Mo Risk	S* (%)	S Risk	Risk of Cu Antagonism
RMH	4.27	High	0.17	Moderate	High risk – Mo well above threshold
St. Paul	4	High	0.19	Moderate	High risk – Mo and S
Nanton	3.15	High	0.19	Moderate	High risk – Mo and S
Red Deer	3.04	High	0.18	Moderate	Elevated risk – Mo above threshold
Mayerthorpe	2.32	Moderate	0.22	High	Elevated risk – S above threshold
Med Hat	2.21	Moderate	0.14	Low	Low risk
La Crete	2.03	Low	0.23	High	Elevated risk – S above threshold
Manning	1.96	Low	0.23	High	Elevated risk – S above threshold
Hanna	1.61	Low	0.17	Moderate	Low risk

*May sulphur data, representing the greatest risk period.

Based on regional forage mineral data, Rocky Mountain House (4.27 mg/kg Mo, 0.17% S) and St. Paul (4 mg/kg Mo, 0.19% S), Nanton (3.15 mg/kg Mo, 0.19% S), and Red Deer (3.04 mg/kg Mo, 0.18% S) show elevated risk of Cu antagonism due to molybdenum levels above 3 mg/kg DM combined with moderate sulfur concentrations (Table 31). Similarly, La Crete, Manning, and Mayerthorpe show moderate risk, reflecting sulfur levels approaching or exceeding 0.2% DM. In contrast, Hanna and Medicine Hat have low molybdenum and sulfur concentrations and thus present a low risk. It is important to note that elevated sulfur (>0.2% DM) exacerbates copper antagonism even when molybdenum is low (McDowell, 2003). Given the low absorption efficiency of copper in ruminants and the presence of antagonistic minerals, the use of chelated copper supplements—which are more stable and less reactive with antagonists—can be an effective strategy to improve copper status in animals at risk.

Manganese

Region (p<2e-16), sampling time (p = 2.08e-09), and the interaction between the two (p = 1.53e-07) all have a significant effect on the manganese levels in pasture forage. Year (p = 0.378) and the interaction between region and year (p = 0.833) do not appear to be significant factors.

Manganese concentrations in forage increased seasonally across most regions, with the highest values observed in October. Central and northern areas like Rocky Mountain House and Manning consistently showed higher Mn levels, likely due to soil conditions and the presence of legumes such as alfalfa. Southern regions, particularly Medicine Hat and Nanton, had the lowest levels. Most samples exceeded the beef cattle requirement of 40 mg/kg DM (NRC, 2016), however taking into consideration the low absorption rate, supplementation is across the province is recommended.

Manganese in May

Manganese concentrations in May varied widely across regions, Table 32 shows Rocky Mountain House had the highest mean Mn concentration at 104.56 mg/kg ± 49.03 SD, followed by Manning (83.14 mg/kg ± 52.31 SD) and Hanna (75.17 mg/kg ± 30.13 SD). Regions such as Med Hat (37.48 mg/kg ± 7.47 SD), Nanton (40.65 mg/kg ± 12.25 SD), and Red Deer (45.79 mg/kg ± 23.60 SD) had the lowest concentrations, approaching or slightly exceeding the minimum requirement for beef cattle (40 mg/kg DM; NRC, 2016). Standard deviations were substantial in some areas, such as Rocky Mountain House (49.03) and Manning (52.31), indicating significant variability within sites.

Table 32. Mean forage Manganese concentrations (mg/kg DM) by region in Alberta during May sampling, with standard deviation, standard error, and range.

	Manganese	Groups	std	se	Min	Max
RMH	104.56	a	49.03	6.13	37.15	215.90
Manning	83.14	ab	52.31	6.13	24.34	200.79
Hanna	75.17	bc	30.13	6.02	38.00	180.35
LaCrete	56.52	bcd	23.47	6.37	25.72	110.97
StPaul	49.89	cd	27.54	7.50	24.98	142.02
Mayerthorpe	48.28	d	27.96	5.91	23.02	164.86
RedDeer	45.79	d	23.60	6.13	27.97	127.40
Nanton	40.65	d	12.25	5.91	21.11	63.35
MedHat	37.48	d	7.74	6.79	27.69	55.49

Manganese in August

Manganese concentrations remained elevated in Rocky Mountain House (110.60 mg/kg) and Manning (103.51 mg/kg) in August, accompanied by increased variability (SDs of 68.18 and 77.61, respectively), As shown in Table 33. In contrast, Nanton (35.44 mg/kg ± 40.65 SD) and Medicine Hat (39.29 mg/kg ± 7.47 SD) continued to show the lowest levels. With the exception of these two southern regions, all areas experienced an increase in Mn from May to August. The rise in Mn may be linked to plant senescence and declining moisture content. Notably, standard deviations increased across all regions, suggesting a growing disparity in Mn content among pastures as the season progressed.

Table 33. Mean forage Manganese concentrations (mg/kg DM) by region in Alberta during August sampling, with standard deviation, standard error, and range.

	Manganese	groups	std	se	Min	Max
RMH	110.60	a	68.18	8.26	25.95	220.15
Manning	103.51	a	77.61	8.42	30.26	347.07
LaCrete	75.94	ab	41.29	8.76	19.96	221.40
Hanna	64.19	bc	28.24	8.26	33.11	163.29
Mayerthorpe	62.10	bc	30.61	7.97	25.91	159.50
StPaul	58.92	bc	28.68	10.12	31.98	132.08
RedDeer	48.91	bc	30.33	8.42	14.21	146.70
MedHat	39.29	bc	14.56	9.15	13.11	74.95
Nanton	35.44	c	12.92	7.97	17.79	73.80

Manganese in October

Table 34 Mean forage Manganese concentrations (mg/kg DM) by region in Alberta during October sampling, with standard deviation, standard error, and range.

	Manganese	groups	std	se	Min	Max
RMH	168.94	a	98.53	11.62	26.05	332.73
Manning	117.59	ab	82.58	11.86	36.43	347.22
Mayerthorpe	114.94	b	71.11	10.78	19.70	330.84
LaCrete	95.63	bc	52.49	12.38	36.53	227.42
Hanna	88.75	bcd	35.94	10.98	37.25	150.45
StPaul	84.12	bcd	35.19	13.69	44.15	165.77
RedDeer	71.83	bcd	46.65	11.39	35.57	225.79
MedHat	48.40	cd	15.43	12.38	27.80	81.36
Nanton	42.36	d	24.81	10.78	11.37	135.70

In October, forage Mn concentrations peaked in many areas, particularly Rocky Mountain House (168.94 mg/kg ± 98.53 SD), Manning (117.59 mg/kg ± 82.58 SD), and Mayerthorpe (114.94 mg/kg ± 71.11 SD). These increases likely reflect seasonal shifts in plant physiology or species composition. Even traditionally lower-Mn areas like Med Hat (48.40 mg/kg ± 15.43 SD) and Nanton (42.36 mg/kg ± 24.81 SD) were above the NRC requirement, though availability is expected to be poor in the highly lignified forage. Standard deviations remained high in several regions indicating persistent within-site variation.

Manganese Discussion

Manganese concentrations in forage across Alberta exhibited clear regional patterns and notable seasonal variation. Rocky Mountain House and Manning consistently showed the highest Mn levels throughout the growing season, while southern and eastern regions such as Nanton and Medicine Hat remained among the lowest. These findings align with previous research indicating that Mn content in forage is strongly influenced by soil characteristics, pH, and plant species composition (Schlegel et al., 2016).

Plant tissue analysis provides a reliable reflection of Mn availability in the soil, availability generally increases as soil pH decreases, particularly within the acidic range of pH 5 to 6 (Obeng et al., 2024). This is evident in Alberta's soil pH distribution (Figure 1), where the more acidic soils in northern and central regions such as RMH and Manning correspond to higher Mn concentrations. Conversely, southern regions like Red Deer, Nanton, and Medicine Hat, characterized by more alkaline soils, had lower forage Mn levels.

Organic matter further influences Mn dynamics; soils rich in organic material support microbial oxidation of Mn^{2+} to less soluble forms, reducing plant availability (Schulte & Kelling, 1999). Soil moisture and aeration also affect Mn solubility. Under prolonged waterlogged conditions, microbial activity can reduce manganese oxides to soluble Mn^{2+} forms, temporarily increasing plant-available Mn; however, this form is prone to leaching, which can lead to long-term soil Mn depletion (Sparrow and Uren, 2014).

Seasonally, Mn concentrations generally increased from May to October, with the exception of Medicine Hat and Nanton, which remained low. This pattern is likely influenced by a combination of plant physiological factors and soil conditions. Manganese uptake occurs primarily during early vegetative growth, when root activity is high, but can continue throughout the growing season if Mn remains available in the soil. However, Mn is relatively immobile within the plant, meaning that ongoing uptake is required to supply developing tissues (Jia 2021).

In terms of nutritional sufficiency, most regions exceeded the beef cattle Mn requirement of 40 mg/kg dry matter by October (NRC, 2016). However, early in the season (May and August), Nanton and Medicine Hat hovered near or below this threshold. Manganese in plants is predominantly stored in the cell walls, particularly bound to pectin and other structural carbohydrates. It also accumulates in vacuoles and, to a lesser extent, participates in enzymatic systems within chloroplasts and mitochondria (Broadley et al., 2012). Because a large portion of Mn is compartmentalized in structural forms or complexed with organic acids, it is not readily released during digestion, particularly in ruminants where solubility and mineral form are critical for absorption (Tedeschi et al., 2023).

In addition, high dietary levels of iron, calcium, and phosphorus can compete with Mn for transporters in the intestinal lining, further limiting its uptake (Spears, 2003). This competitive inhibition, combined with the chemical inaccessibility of plant-bound Mn, contributes to the typically low absorption rates of 1–10% reported in ruminants, even when total dietary Mn appears adequate.

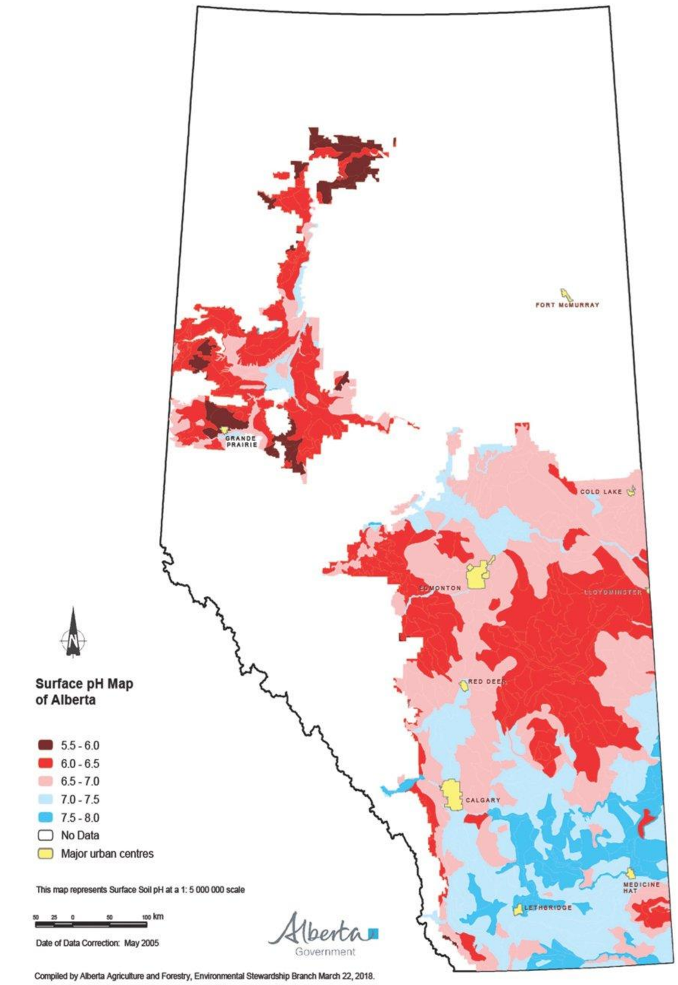

Figure 1. Surface pH Map of Alberta

As a result, dietary assessments based solely on total Mn concentrations in forage may overestimate actual bioavailable Mn for cattle. This is particularly relevant during early-season grazing when forage mineral interactions and plant structure are more dynamic, potentially compounding the risk of subclinical Mn deficiency.

Zinc

Region is a significant factor affecting Zn levels ($p<2e-16$), while sampling time does not have a significant effect ($p = 0.164$). The interaction between sampling time and region suggests that the impact of sampling time may vary depending on the region ($p = 0.004$).

Zinc Variability due to Region

Zinc concentrations in forage across Alberta showed significant regional variation. La Crete (33.77 mg/kg ± 15.73 SD) and Mayerthorpe (32.02 mg/kg ± 25.82 SD) had the highest mean Zn levels, significantly greater than southern regions such as Medicine Hat (16.82 mg/kg ± 6.46 SD) and Red Deer (19.23 mg/kg ± 9.99 SD).

Table 35. Mean Zinc concentrations (mg/kg DM) in forage samples across nine regions in Alberta.

	Zinc	Groups	std	se	Min	Max
LaCrete	33.77	a	15.73	1.50	10.84	110.76
Mayerthorpe	32.02	a	25.82	1.41	13.29	234.68
RMH	27.89	ab	11.52	1.47	12.51	63.55
Manning	25.25	bc	10.16	1.48	12.34	88.20
Hanna	23.59	bc	8.70	1.44	8.45	55.60
StPaul	23.02	bcd	8.07	1.80	10.77	55.13
Nanton	20.16	cd	7.09	1.41	7.58	39.88
RedDeer	19.23	cd	9.99	1.48	6.05	90.82
MedHat	16.82	d	6.46	1.62	6.87	33.41

The variability within regions was substantial, especially in Mayerthorpe (SD = 25.82) and La Crete (SD = 15.73), indicating heterogeneous Zn distribution among pastures. Zinc concentrations ranged broadly from a minimum of around 6 mg/kg in Medicine Hat to a maximum exceeding 230 mg/kg in Mayerthorpe, highlighting localized soil or plant species effects.

Zinc Between Years

Year does not have a significant effect on Zinc levels ($p = 0.573$), meaning the levels of zinc do not vary significantly between years across all regions. There is a significant interaction between Region and Year ($p = 0.008$), meaning the effect of region on zinc levels might differ between the years. This suggests that the pattern of Zinc levels across regions could change from one year to the next.

Zinc Discussion

Zinc is an essential trace mineral involved in numerous biological processes including immune function, growth, reproduction, and enzyme activity (NRC, 2016). The beef cattle dietary Zn requirement is generally estimated at approximately 30 mg/kg dry matter (NRC, 2016), though physiological demands can increase during growth, lactation, or stress.

In this study, forage Zn concentrations varied regionally across Alberta, with northern sites like La Crete and Mayerthorpe exceeding the 30 mg/kg target on average, while southern locations such as Medicine Hat and Red Deer fell below this benchmark. Rocky Mountain House and Manning showed intermediate Zn levels near the recommended requirement. These findings align with soil and forage mineral trends previously reported, where Zn availability often correlates with soil type, pH, and organic matter content (Schlegel et al., 2016). Taking into consideration Zn absorption rates in ruminants typically range from 10% to 30% of dietary intake depending on source and diet composition (Spears, 2003), Zn from forage alone will not be sufficient to meet the requirements of cattle in any region.

There is some evidence to suggest bioavailability of Zn may be limited by antagonistic interactions in the diet, particularly with elements like iron, calcium, and phosphorus, which some studies have shown to reduce Zn absorption (Spears, 2003; McDowell, 2003).

Given the variability within regions and potential bioavailability challenges, supplementing Zn is recommended. Where there are high antagonism risks, targeted supplementation, preferably using bioavailable sources such as chelated Zn, may be necessary to avoid subclinical deficiencies that can impair animal performance and health.

Selenium

Selenium levels in pasture forage are significantly impacted by region ($p < 2e-16$), but sampling time ($p = 0.253$) and the interaction between sampling time and region ($p = 0.939$) do not appear to be significant.

Regional Differences in Selenium

Selenium concentrations in forage demonstrated significant spatial variability across Alberta regions, as detailed in Table 36. The highest mean Se concentration was recorded at Medicine Hat (0.80 mg/kg ± 0.43 SD), which was statistically greater ($p < 0.05$) than all other sites. Red Deer (0.47 mg/kg ± 0.31) and Hanna (0.33 mg/kg ± 0.19 SD) exhibited intermediate levels, while St. Paul, Manning, Nanton, La Crete, RMH, and Mayerthorpe ranged from 0.23 to 0.12 mg/kg DM.

Table 36. Mean Selenium concentrations (mg/kg DM) in forage samples across nine regions in Alberta.

	Selenium	Groups	std	se	Min	Max
MedHat	0.80	a	0.43	0.05	0.25	1.79
RedDeer	0.47	b	0.31	0.04	0.12	1.45
Hanna	0.33	bc	0.19	0.04	0.09	0.84
StPaul	0.23	cd	0.17	0.05	0.06	0.64
Manning	0.22	cd	0.27	0.04	0.02	1.16
Nanton	0.16	cd	0.15	0.04	0.05	0.50
LaCrete	0.15	cd	0.15	0.04	0.02	0.50
RMH	0.15	cd	0.15	0.04	0.02	0.50
Mayerthorpe	0.12	d	0.14	0.04	0.04	0.50

Analysis of variance indicated no significant temporal variation in Se concentrations across sampling periods, underscoring regional soil and environmental factors as the primary determinants of forage Se content (McDowell, 2003; NRC, 2016). The observed spatial gradient, with elevated Se concentrations in southern Alberta relative to northern and central regions, is consistent with previous findings linking soil selenium availability to regional geology and soil characteristics (Suttle, 2010).

Selenium Between Years

No difference in Se was measured between years ($p = 0.753$) and the interaction between region and year was not significant ($p = 0.808$).

Selenium Discussion

Selenium in forages occurs mainly in organic amino acid forms, predominantly selenomethionine, and to a lesser extent selenocysteine, both of which are incorporated into plant proteins. In contrast, most supplemental selenium for livestock is supplied as inorganic salts (sodium selenite or selenate; McDowall, 2003). In nonruminant models, true absorption of selenomethionine commonly ranges from approximately 70% to over 90%, whereas inorganic selenite tends to be lower (~40–60%), illustrating the inherently higher uptake potential of amino acid–bound Se (McDowell, 2003; Mehdi & Dufrasne, 2016). In ruminants, rumen microbes can reduce selenite/selenate to less soluble forms and sequester selenium into microbial biomass, generally lowering absorption of inorganic sources. Reported apparent absorption values in cattle and sheep frequently fall in the ~30–60% range for forage/organic Se and ~20–40% for inorganic selenite, but outcomes vary with diet fermentability, sulfur load, and Se status (Koenig et al., 1997; Spears, 2003; Hendawy et al., 2022). Organic Se sources (e.g., selenized yeast) typically produce higher blood, milk, or tissue Se responses than equal amounts of selenite in cattle under many, but not all, feeding situations, underscoring that diet context matters as much as chemical form (NRC, 2016).

In the present study, only Medicine Hat and Red Deer (east of Highway 2) had forage selenium concentrations that may be sufficient to meet beef cattle requirements (≈0.10 mg Se/kg DM) without supplementation. These findings align with regional geochemical evidence showing elevated Se in portions of southeastern Alberta influenced by Se-enriched Cretaceous shale parent materials (Campbell et al., 1995). Where forage Se is high, over-supplementation becomes a management concern because Se lacks strong homeostatic down-regulation of absorption and can accumulate in tissues (Mehdi & Dufrasne, 2016; NRC, 2016).

Selenium interacts antagonistically with S due to chemical similarity; elevated dietary S can depress Se absorption and reduce incorporation into selenoproteins. Spears (2003) emphasized reduced Se bioavailability with rising S load, and subsequent reviews have reinforced the importance of evaluating S when interpreting herd Se status (Mehdi & Dufrasne, 2016). This interaction is particularly relevant in northern Alberta regions such as La Crête and Manning, where forage S levels in our dataset were elevated. Additional S may enter the diet via sulfur-containing fly-control or garlic-fortified products used during the summer grazing season, potentially compounding antagonism. These inputs may further reduce functional Se status even when total dietary Se appears adequate (Spears, 2003; Hendawy et al., 2022).

Molybdenum

Molybdenum levels in pasture grass were influenced by the region (p<0.01) but were not impacted by sampling time (p = 0.27) or the interaction between sampling time and region (p = 0.735).

Regional Affects on Molybdenum

Molybdenum concentrations varied significantly across regions ($p < 0.05$), with the highest mean values observed in the Rocky Mountain House and St. Paul regions (Table 37). Rocky Mountain House had the highest average Mo concentration at 4.27 mg/kg ± 4.17 SD, which was significantly greater than all other regions except St. Paul (4.00 mg/kg, $p > 0.05$).

Table 37. Mean Molybdenum concentrations (mg/kg DM) in forage samples across nine regions in Alberta.

	Molybdenum	Groups	std	se	Min	Max
RMH	4.27	a	4.17	0.22	0	20.65
StPaul	4.00	ab	2.25	0.26	1.16	11.96
Nanton	3.15	bc	1.75	0.20	1.15	9.14
RedDeer	3.04	bc	1.16	0.21	1.03	6.35
Mayerthorpe	2.32	cd	1.49	0.21	0	7.08
MedHat	2.21	cd	0.94	0.23	0.74	5.45
LaCrete	2.03	d	1.06	0.21	0	6.03
Manning	1.96	d	1.18	0.21	0	8.69
Hanna	1.61	d	0.57	0.21	0.54	3.28

Regions in the central and southern parts of the province (Nanton, Red Deer, Mayerthorpe, and Medicine Hat) had intermediate Mo concentrations ranging from 3.15 to 2.21 mg/kg, forming a statistically distinct group from the highest and lowest regions. Nanton and Red Deer (3.15 and 3.04 mg/kg, respectively) were not significantly different from each other or from St. Paul but were higher than La Crete, Manning, and Hanna ($p < 0.05$).

The lowest Molybdenum concentrations were detected in the northern and eastern regions of La Crete, Manning, and Hanna, with mean values of 2.03, 1.96, and 1.61 mg/kg, respectively. These values formed a distinct group, significantly lower than Rocky Mountain House, St. Paul, and Nanton. Hanna had the lowest observed concentration overall.

Within-region variability was notable in Rocky Mountain House, where values ranged from 0 to 20.65 mg/kg, indicating potential localized accumulation. In contrast, Hanna showed the least variability (range: 0.54–3.28 mg/kg).

Molybdenum Between Years

An ANOVA test showed the difference in molybdenum measured between years was significant ($p = 0.042$) however, upon running a post- hoc test (Tukey's Test), all regions showed no significant difference between years. It is believed that the significant p-value is coming from sub datasets and is not reflective of the regions as a whole.

The region: year interaction is not significant ($p = 0.1481$), meaning that the effect of changing environmental conditions between years impacts all regions similarly.

Molybdenum Discussion

Molybdenum concentrations in forage varied significantly across the nine sampled regions of Alberta, with values ranging from 1.61 to 4.27 mg/kg dry matter (DM). The highest concentrations were observed in Rocky Mountain House and St. Paul, both exceeding 4.0 mg/kg, while the lowest levels were found in Hanna, Manning, and La Crete (<2.0 mg/kg). This regional variability is likely influenced by underlying soil characteristics, including pH and organic matter. Alkaline soils and those derived from shale or sedimentary rock formations are known to increase Mo availability to plants (Gupta & Lipsett, 1981; Kabata-Pendias, 2011). In particular, the presence of elevated Mo values in Rocky Mountain House may reflect localized geological or anthropogenic enrichment such as manure application or industrial contamination (Alloway, 2013).

From a nutritional perspective, Mo plays a complex role in ruminant health due to its interaction with Cu and S. While Mo itself is an essential trace element, excessive intake can lead to secondary Cu deficiency through the formation of thiomolybdate complexes in the rumen, which impair Cu absorption (Suttle, 2010). The generally accepted upper limit for Mo in forages to avoid antagonistic effects is approximately 3.0 mg/kg DM (McDowell, 2003; Kincaid, 2000). Several regions in this study (including Rocky Mountain House, St. Paul, Nanton, and Red Deer) had mean Mo concentrations at or above this threshold, indicating a potential risk for Cu deficiency in cattle grazing these pastures.

Importantly, the substantial within-region variability, particularly in Rocky Mountain House (range: 0–20.65 mg/kg), highlights the spatial heterogeneity of Mo in forage. This suggests that regional averages may not fully capture the risk of mineral imbalance on individual pastures. In contrast, regions such as Hanna, Manning, and La Crete consistently exhibited low Mo concentrations, suggesting minimal antagonistic risk in those locations under typical grazing conditions.

In regions with elevated Mo, producers may need to increase Cu supplementation and ensure sulfur levels in feed and water are not excessive. Strategies such as offering Cu supplements with higher bioavailability (e.g., Cu proteinate) may help mitigate Mo-induced Cu deficiency (Kincaid, 2000; NRC, 2016).

Iron

Region ($p < 0.001$), sampling time ($p < 0.001$), and the interaction between the two ($p < 0.001$) were found to be important factors affecting Fe concentrations. Throughout the season we observed a decrease in Fe from May to August, followed by a greater increase from August to October. Our results show Fe levels were greatest in the October sampling period.

Iron in May

In May, significant regional differences were observed ($p < 0.05$). Hanna (108 mg/kg ± 33 SD), Medicine Hat (106 mg/kg ± 27 SD), and Nanton (92 mg/kg ± 26 SD) had the highest mean Fe concentrations, while Rocky Mountain House showed the lowest at 70 mg/kg ± 18 SD (Table 38).

Table 38. Mean forage iron concentrations (mg/kg DM) by region in Alberta during May sampling, with standard deviation, standard error, and range.

	Iron	groups	std	se	Min	Max
Hanna	108	a	33	6	67	186
MedHat	106	a	27	6	68	174
Nanton	92	ab	26	5	55	173
LaCrete	88	abc	26	5	64	179
Manning	82	bc	18	3	62	135
StPaul	80	bc	25	6	54	139
Mayerthorpe	80	bc	31	6	47	190
RedDeer	78	bc	18	3	48	121
RMH	70	c	13	2	48	103

Iron in August

In August, no statistically significant regional differences were detected (Table 39). Mean Fe values ranged from 75 mg/kg ± 26 SD (Red Deer) to 96 mg/kg ± 34 SD (Hanna), but all regions fell within the same statistical grouping, indicating a seasonal convergence in forage Fe levels during late summer.

Table 39. Mean forage iron concentrations (mg/kg DM) by region in Alberta during August sampling, with standard deviation, standard error, and range.

	Iron	groups	std	se	Min	Max
Hanna	96	a	34	6	39	197
LaCrete	91	a	32	6	53	181
StPaul	85	a	37	9	46	185
RMH	85	a	42	8	34	176
Nanton	82	a	32	6	35	198
MedHat	81	a	44	10	32	168
Manning	79	a	26	5	39	172
Mayerthorpe	77	a	25	5	45	154
RedDeer	75	a	26	5	22	136

Iron in October

By October, regional differences re-emerged. Mayerthorpe (145 mg/kg ± 36 SD) had the highest Fe concentration and was significantly greater than Medicine Hat (105 mg/kg ± 49 SD; $p < 0.05$). Most other regions, including La Crete, Hanna, and St. Paul, showed elevated Fe values in the 120–140 mg/kg range, although these differences were not statistically significant from one another.

Table 40. Mean forage iron concentrations (mg/kg DM) by region in Alberta during October sampling, with standard deviation, standard error, and range.

	Iron	groups	std	se	Min	Max
Mayerthorpe	145	a	36	7	87	210
LaCrete	141	ab	35	7	81	206
Hanna	133	ab	46	10	54	209
StPaul	130	ab	36	9	88	188
RedDeer	127	ab	42	9	75	206
Manning	121	ab	38	8	34	191
Nanton	114	ab	24	4	65	155
RMH	111	ab	35	7	52	196
MedHat	105	b	49	12	47	198

Iron between years

Interannual comparisons revealed significant year effects in three regions. In Rocky Mountain House, Fe concentrations peaked in 2023 (112.66 mg/kg DM), declined moderately in 2021 (102.87 mg/kg DM), and were significantly lower in 2024 (71.42 mg/kg DM; $p < 0.05$). In Hanna, Fe was also significantly lower in 2024 (84.04 mg/kg DM) compared to both 2021 and 2023 (137.27 and 144.59 mg/kg DM, respectively). Medicine Hat experienced the most substantial year-on-year drop, with Fe decreasing from 186.53 mg/kg DM in 2023 to 77.41 mg/kg DM in 2024. Notably, 2024 was consistently lower in iron concentration across all regions where a significant difference was measured, suggesting a potential province-wide shift in forage Fe availability during that year. In contrast, no significant year-to-year differences were observed in La Crete, Manning, St. Paul, Mayerthorpe, Red Deer, or Nanton. These patterns may reflect region-specific environmental factors or broader climatic influences such as precipitation variability, drought intensity, or changes in plant growth stage at time of sampling, all of which can affect micronutrient uptake and accumulation in forage.

Iron Discussion

Iron concentrations in forage samples varied both regionally and seasonally across Alberta, with mean values ranging from 70 mg/kg to 145 mg/kg dry matter (DM). These concentrations were consistently above the minimum dietary requirement for beef cattle, which is approximately 50 mg/kg DM (NRC, 2016), indicating that iron deficiency is unlikely to be a concern in any of the regions or time points evaluated in this study.

Table 41. Post-hoc Tukey's test showing significant and numerical differences in iron content of pasture grass in years 2021,2023, and 2024.

Post-hoc Tukey's test for RMH :		
Year	Iron	Groups
2021	102.87	ab
2023	112.66	a
2024	71.42	b
Post-hoc Tukey's test for Hanna :		
Year	Iron	Groups
2021	137.27	a
2023	144.59	a
2024	84.04	b
Post-hoc Tukey's test for MedHat :		
Year	Iron	Groups
2023	186.53	a
2024	77.41	b
No significant difference in years for LaCrete		
No significant difference in years for Manning		
No significant difference in years for StPaul		
No significant difference in years for Mayerthorpe		
No significant difference in years for RedDeer		
No significant difference in years for Nanton		

Significant regional differences were observed in the May and October sampling periods, while August exhibited relatively uniform Fe levels across regions. August also represented a seasonal low point in Fe concentrations, with reduced variability among regions, potentially reflecting plant phenology, dilution effects due to active growth, or lower soil contamination during mid-season sampling.

The seasonal increase in Fe observed in October may be attributable to a combination of factors, including increased senescence of forage species, concentration of minerals in residual biomass, and greater exposure to soil during sampling due to reduced plant height and biomass. Similar seasonal patterns have been reported in other forage studies, where Fe concentrations increased in late-season samples, likely as a result of soil splash and plant aging (Reuter & Robinson, 1997).

While the Fe concentrations observed in this study were well below toxicity thresholds for cattle (typically considered >500 mg/kg DM), elevated Fe can interfere with the bioavailability of other essential trace elements. Iron competes with copper and manganese for absorption sites in the gastrointestinal tract, potentially exacerbating existing marginal deficiencies of these minerals (Goff, 2018; McDowell, 2003). This is particularly relevant in regions where antagonistic interactions may already exist due to high levels of molybdenum or sulfur. For example, in Mayerthorpe and La Crete, high Fe was observed in October, and co-occurring high Mo or S could compound the risk of Cu antagonism.

Although forage Fe levels alone are unlikely to cause clinical toxicity, the potential for indirect effects on trace mineral balance warrants attention.

Weather

Weather data were summarized for each study location Alberta Climate Information Service records (https://acis.alberta.ca/acis/township-data-viewer.jsp) from weather stations situated within the same townships as the forage sampling sites. Measurements included seasonal average air temperature (°C; Figure 3) and total precipitation (mm; Figure 2) across the growing season (May–October) for 2021, 2023, and 2024.

2021 Season

In 2021, growing conditions were cooler and drier in many areas relative to subsequent years. Average temperatures ranged from 0.28°C in La Crete to 5.53°C in Nanton, with most regions recording values between 2–4°C. Precipitation was variable but generally lower, particularly in the southeast; for example, Medicine Hat received only 170.6 mm of rainfall, while Nanton and Rocky Mountain House saw higher totals at 365.9 mm and 376.6 mm, respectively. These conditions likely constrained early forage growth and biomass accumulation, while also slowing plant maturity. Consequently, forage quality may have remained more stable throughout the season, especially in the northern regions.

2023 Season

The 2023 growing season was the warmest across all study years, with average temperatures ranging from 3.10°C in La Crete to 6.66°C in Nanton. Warmer conditions were consistent across the province, and most sites also experienced moderate to high precipitation. Rocky Mountain House and Barrhead exceeded 437 mm, while Medicine Hat remained relatively dry at 155.2 mm. These weather patterns likely promoted rapid early-season growth, followed by accelerated maturation and nutrient dilution in the forage, which is reflected in the steeper mid-season declines in TDN and crude protein observed in several southern and central sites.

2024 Season

In contrast, the 2024 season was cooler and significantly wetter across nearly all locations. Average air temperatures were reduced compared to 2023, ranging from 1.52°C in La Crete to 5.42°C in Nanton. Notably, precipitation increased substantially, with Medicine Hat receiving 382.6 mm, Nanton 442.4 mm, and Hanna 398.7 mm, nearly doubling their 2023 totals. These cooler, wetter conditions delayed plant development early in the season, potentially preserving forage quality into the late summer. However, persistent moisture may have also influenced species composition, favoring cool-season grasses and potentially reducing the proportion of legumes in mixed stands.

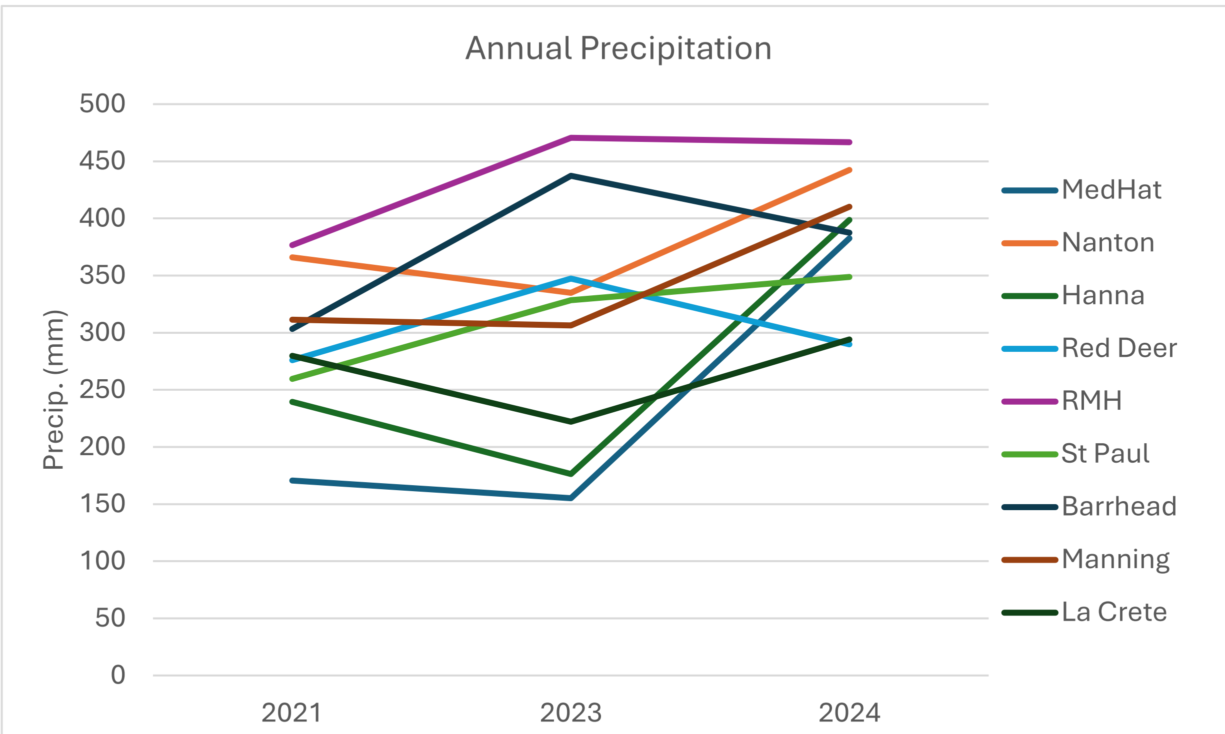

Figure 2. Regional Annual Precipitation in 2021, 2023, and 2024
https://acis.alberta.ca/acis/township-data-viewer.jsp

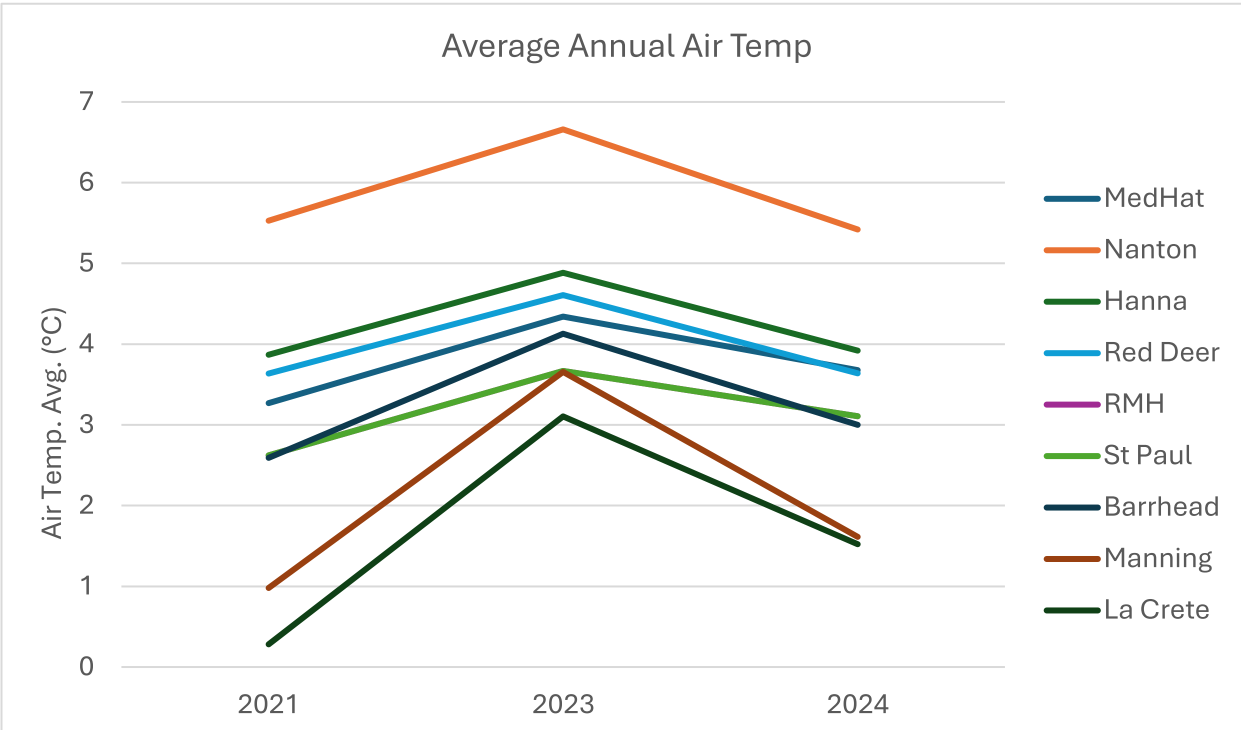

Figure 3. Regional Annual Air temp in 2021, 2023, and 2024.
https://acis.alberta.ca/acis/township-data-viewer.jsp

Conclusion & Recommendations

This study highlights substantial regional and seasonal variability in the nutritional quality of pasture forages across Alberta. While early-season samples generally met the energy, protein, and macro-mineral requirements of beef cows in mid- to late gestation, nutrient concentrations declined as the growing season progressed. By late summer and fall, deficiencies in phosphorus, magnesium, and key trace minerals became increasingly common, particularly in southern and central regions.

Trace mineral adequacy was further complicated by low absorption coefficients. Despite measured concentrations approaching or exceeding dietary requirements in some regions, elements such as copper, zinc, and manganese are subject to poor bioavailability due to both chemical form and antagonistic interactions. High dietary levels of molybdenum, sulfur, and iron are known to impair the uptake and utilization of these trace elements through the formation of insoluble complexes or competitive inhibition at absorption sites. As a result, functional deficiencies may occur even where total dietary supply appears sufficient.

Given these findings, regionally adapted supplementation strategies should be prioritized (particularly in the late growing season) to ensure adequate intake of bioavailable trace minerals and to mitigate the risk of performance losses or subclinical health issues in grazing beef herds.

Table 42. Regional Forage Mineral Risk Assessment and Supplementation Considerations for Beef Cows in Mid-to-Late Gestation (Alberta, 2021–2024).

Region	Main Mineral Concerns	Supplementation Recommendations	Notes / Risks
La Crete	Low Se, High S, Moderate Mo	Supplement Se; Cu supplementation due to Mo-S antagonism	High S may reduce Se bioavailability
Mayerthorpe	Low Se, Moderate S & Mo, Ca:P imbalance	Supplement Se, P; Monitor Cu status	Elevated Fe + Mo risk for Cu antagonism
Rocky Mountain House	Very high Mo (up to 20.65 mg/kg), variable Fe	Aggressive Cu supplementation (high bioavailability forms)	Strong risk of Cu deficiency
Manning	Low Se, Moderate Mo & S, Poor Ca:P ratio	Supplement Se, P; Monitor Cu closely	Mo-S-Cu interactions require attention
Hanna	Seasonal Fe variability, low Zn in Aug	Year-round Cu-Zn-Se supplementation	Monitor mineral shifts during drought or stress
St. Paul	Low Se, Moderate S, borderline Zn & P	Supplement Se, P, Cu	Risk of Cu deficiency
Nanton	Low Se, Moderate Mo, low P & Ca	Supplement Se, P, Ca; Use bioavailable Cu	Early season P supplementation
Red Deer	Low Zn, low Cu, Moderate Mo & S	Supplement Zn, Cu, Se	Potential need for bioavailable Cu
Medicine Hat	Lowest Zn, Fe variability, borderline Ca:P	Reduce Se supplementation; Supplement Zn, Cu	Risk of Se toxicity if oversupplemented

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