

THESIS

CHARACTERIZING THE VITAMIN AND MINERAL STATUS OF FARMED AMERICAN
BISON IN THE UNITED STATES

Submitted by

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ABSTRACT

CHARACTERIZING THE VITAMIN AND MINERAL STATUS OF FARMED AMERICAN BISON IN THE UNITED STATES

The American bison (*Bison bison*) has become increasingly prevalent within the agricultural sector, yet limited research exists on their specific nutritional needs, particularly for vitamins and minerals. Minerals play a critical role in physiological processes like muscle development, reproduction, and enzyme activation, while vitamins act as coenzymes essential for metabolic pathways and immune functions. This study aimed to establish baseline mineral and vitamin concentrations in farmed American bison tissues and to analyze mineral and vitamin contents of feed and water across locations within the United States. Post-mortem samples, including blood, liver, kidney, and muscle, were collected from bison processed at USDA-inspected facilities. Seasonal sampling captured variations in feed and water composition. Tissue samples underwent mineral analysis using inductively coupled plasma-optical emission spectrometry (ICP-OES), while vitamin levels were determined via liquid chromatography-tandem mass spectrometry (LC-MS/MS). To provide context, a scoping review of existing literature on mineral and vitamin concentrations in bison and related species was conducted, yielding weighted means for comparison. Results highlight the nutritional variability across ranches, seasons, ages, and sexes offering foundational data for developing species-specific dietary recommendations. These findings address a critical knowledge gap in farmed American bison mineral and vitamin status, and hopes to drive future research in bison agriculture, enhancing animal health, welfare, and productivity in these farmed settings.

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CHAPTER 1 – VITAMIN AND MINERAL STATUS WITHIN VARIOUS TISSUES OF BISON: A SCOPING REVIEW¹

1. Introduction

The American bison (*Bison bison*), a species with deep cultural and ecological roots in North America, has gained prominence within the agricultural industry over the past decade (Freese et al., 2007; USDA, 2022). As bison populations grow across the United States and Canada, so too does interest in their management from various sectors, including scientific research, tribal communities, and commercial production systems (Galbraith et al., 2014; USDA, 2024). This growing popularity highlights the need for comprehensive knowledge about bison biology and nutrition, particularly in confined or controlled farming environments where traditional grazing patterns are altered (Hawley et al., 1978; Hecker et al., 2021). Most nutritional information available for bison are from wild species on conservations within the United States, as well as similar species (European bison (*Bison bonasus*)) in Polish wildernesses (Richmond et al., 1977; Wolk and Krasinska, 2004). Nutrition is a cornerstone of livestock management, influencing growth, reproduction, and overall health. However, critical gaps remain in understanding the specific vitamin and mineral requirements of bison.

Minerals are essential for numerous physiological processes, including muscle development, reproduction, immune function, and enzymatic activity (Puls, 1994; McDowell, 2006). Despite their importance, studies examining mineral concentrations in bison tissues are limited. Research has primarily focused on macro- and micro-mineral levels in tissues such as liver, kidney, and muscle, often comparing these concentrations to cattle, as well as concerns for extreme toxicities

or deficiencies of minerals which could impair immune function and metabolic processes essential for growth and reproduction (Marchello et al., 1989; Galbraith et al., 2006, Durkalec et al., 2018). (Durkalec et al., 2018).

Vitamins, though equally vital, are even less studied in bison. Acting as coenzymes in metabolic reactions, vitamins such as A, E, and K are critical for immune function, growth, and reproduction (Wagner et al., 2023; Smith, 2023). Most research on vitamins in bison has focused on meat quality, particularly the role of vitamins A and E in enhancing meat color stability and nutrient profiles (Driskell et al., 2004; Galbraith et al., 2016). While these studies contribute to understanding bison meat's nutritional value, they offer limited insights into the vitamins' role in overall animal health and production efficiency. Research in beef cattle has highlighted the importance of vitamins in maintaining immune function and mitigating stress, yet similar investigations in bison are scarce (McDowell, 2006). Moreover, the interactions between vitamins and minerals—such as the interplay between vitamin E and selenium—remain unexplored in bison, further underscoring the need for comprehensive nutritional studies.

One of the challenges in developing dietary recommendations for bison is that current guidelines are often extrapolated from cattle research (Puls, 1994; NFACC, 2017). However, bison differ significantly from cattle in terms of digestive physiology, metabolic rates, and natural diets, which may affect their nutrient requirements (Delgiudice et al., 1994; Saskatchewan Agriculture & Food, 1999). For example, bison are adapted to forage diverse plant species and may have evolved unique mechanisms to process nutrients (Delgiudice et al., 1994; Raynor et al., 2015). Without species-specific data, the nutritional programs designed for bison may fail to address their unique needs, potentially compromising their health and welfare. The Scientific Committee responsible for Canada's Bison Code of Practice identified this gap in their

2016 report, emphasizing the importance of research into vitamin and mineral requirements for farmed bison (NFACC, 2017).

As bison farming continues to expand, there is an urgent need to fill these knowledge gaps to ensure sustainable, ethical, and productive management practices. Establishing baseline vitamin and mineral concentrations in bison tissues is a critical step toward developing accurate dietary recommendations. Furthermore, understanding how environmental factors, such as seasonal changes and diet composition, influence nutrient profiles can help optimize bison health and production outcomes. The objectives of this scoping review is 1) to synthesize existing research on vitamin and mineral concentrations in various tissues of American bison (*Bison bison*) and European bison (*Bison bonasus*), 2) identify gaps in knowledge regarding their nutritional requirements and effects of a variety of other factors, and 3) provide a foundation for developing species-specific dietary guidelines that aim to support health, growth, and welfare.

2. Methods

This scoping review was completed using the methodological framework detailed by Arksey and O'Malley (2005) and expanded by Levac et al. (2010) and applied the reporting guidelines from the PRISMA checklist and flow diagram (Page et al., 2021).

2.1. Eligibility Criteria

2.1.1. Population, Factors, & Outcomes

This scoping review focuses on two closely related bison species: the American bison (*Bison bison*) and the European bison (*Bison bonasus*). Their shared genus (*Bison*) suggests significant similarities, making them both interesting subjects for this study. Furthermore, the review encompasses both free-range and captive bison populations of all ages and sexes. The

search prioritized studies investigating vitamin and mineral concentrations within various tissue types including all known vitamins and both macro and micro minerals. Tissue samples included were both external (e.g., skin, hair, and hooves) and internal structures (e.g., organs, blood, and bone) obtained either from a live or recently deceased animals.

2.1.2. Limitations

Only papers with at least an abstract available in English were considered. Additionally, the focus was strictly on primary research, eliminating the insights from reviews or secondary analyses. There are many terms used for bison. While "buffalo" is sometimes used interchangeably with "bison," papers solely using "buffalo" without clarifying the species were meticulously examined to ensure the focus of the paper was on *Bison bison* or *Bison bonasus*. If the origin of the term "buffalo" was unclear and could not be definitively identified as referring to bison, the study was excluded from this review. Finally, the analysis solely considered raw or uncooked meat tissue samples, eliminating studies that analyzed solely cooked bison meat. These limitations were necessary to maintain a clear focus and reliable data set for the paper.

2.2. Search

2.2.1. Information Sources

To ensure a comprehensive yet focused search, information for this paper was sourced through a multi-pronged approach. First, a consultation with a scoping review-knowledgeable librarian helped refine our search strategy. Three academic databases were searched for this review: PubMed, CAB Abstract, and Web of Science. Filters were applied within each database to limit results to articles published in English and designated as primary research (excluding reviews or meta-analyses). The core search concepts combined terms related to the target

population ("American bison" OR "European bison") with the topic of interest ("vitamin* AND mineral* AND tissue*"). Finally, to ensure data accuracy, any studies referencing "water buffalo" were excluded from further analysis. This comprehensive search was conducted on March 1st, 2024.

2.2.2. Search Strategy

Consulting with a librarian allowed for refining the search strategy for this paper. Initial testing on PubMed, using a few key reference papers for comparison, revealed a significant issue. The term "buffalo" captured both many irrelevant and relevant studies, particularly compared to other databases like CAB Abstract or Web of Science. This highlighted the need for database-specific adjustments. Consequently, we developed tailored search strings for each database, ensuring optimal retrieval of relevant studies while minimizing the inclusion of unwanted "buffalo" references. **Table 1.1** includes the databases utilized, as well as the complete search string used for procurement of articles for the scoping review. Databases and search string for the scoping review covering mineral and vitamin statuses within tissues of bison.

Table 1.1. Databases and search string for a scoping review covering vitamin and mineral concentrations within various tissues in bison

Database ¹	Interface	Dates Included ²
Cab Abstracts	CABI	1969-2023
PubMed	NCBI	1968-2023
Web of Science Core Collection	Web of Science	1940-2023

Search String (All Databases)³

("Bison" OR "American Buffalo*")AND("trace minerals" OR "trace element*" OR "macro-element*" OR "microelement*" OR "vitamin*" OR "mineral*" OR "macro-mineral*" OR "micronutrient*" OR "macronutrient*" OR "digest*" OR "calcium" OR "phosphorus" OR "magnesium" OR "potassium" OR "sodium" OR "cobalt" OR "copper" OR "iodine" OR "iron" OR "selenium" OR "zinc" OR "cobalamin") AND ("require*" OR "stat*" OR "nutrient composition" OR "concentration*" OR "toxicit*" OR "deficien*" OR "nutrient deprivation" OR "nutri*" OR "supplement*" OR "diet" OR "ingest*" OR "ration*" OR "performance*")*

¹ "Peer Reviewed" was applied as a filter on all database searches

² Dates were reported by each database's respective preset year range. Data exclusion was not applied as a filter for all searches

2.2.3. Selection of Sources

After each search was conducted, all retrieved articles were downloaded and imported into a reference management software (Zotero, Fairfax, VA). Following this, a two-stage screening process was implemented. In the first stage, two researchers independently reviewed all article titles, discarding any studies clearly irrelevant to the topic (e.g., focusing on water buffalo). Next, the remaining articles underwent a more detailed review of abstracts and full text, again conducted independently by both researchers using inclusion and exclusion criteria (**Table 1.2**). Disagreements on article inclusion were resolved through discussion to ensure consensus. Finally, any relevant studies not captured by the database searches and found via bibliographies searches from original database search results were (n=6) manually added to Zotero, ensuring a comprehensive pool of potential sources for the paper.

Table 1.2. Inclusion and exclusion criteria for article screening for the scoping review investigating mineral and vitamin status within tissues in bison

Inclusion Criteria	Exclusion Criteria
<ul style="list-style-type: none">- Population American bison AND/OR European bison- Original Research- Includes mineral AND/OR vitamin concentrations within<ul style="list-style-type: none">o Livero Kidneyo Muscleo Bloodo Hairo Boneo Other organs	<ul style="list-style-type: none">- Population listed as “buffalo” without indication of specific species- Abstract AND text not in English- Not original research (i.e. reviews)- Muscle related articles only about cooked meat

2.3. Data Charting and Synthesis of Results

Data extraction followed a two-step process. First, both reviewers collaboratively defined the key variables of interest to be extracted from the articles. Subsequently, one researcher systematically reviewed each article and extracted the identified variables. All extracted data was then compiled and organized in a Microsoft Excel spreadsheet. To facilitate analysis, the variables were categorized as either predictor or outcome variables. A "predictor" is any variable used to predict the value of another variable, called the "outcome". Additionally, the number of articles investigating each individual variable was documented.

3. Results

3.1. Study Selection

The initial search across PubMed, CAB Abstract, and Web of Science yielded a total of 1,039 articles. Duplicates were eliminated (n = 108). During title screening 872 articles were excluded due to titles indicating irrelevance to the topic or the population of interest. Following a more in-depth text and abstract screening of the 58 articles remaining by two independent reviewers, an additional 13 articles were removed based upon not sampling correct tissue types, not investigating vitamin and mineral concentrations, not a primary research study, or not available in English. To ensure comprehensiveness, 7 relevant studies identified through other means (e.g., reference lists) were manually added. This selection process resulted in a final population of 51 articles deemed suitable for the objective of this scoping review. A flow diagram outlines the study selection process in **Figure 1.1**.

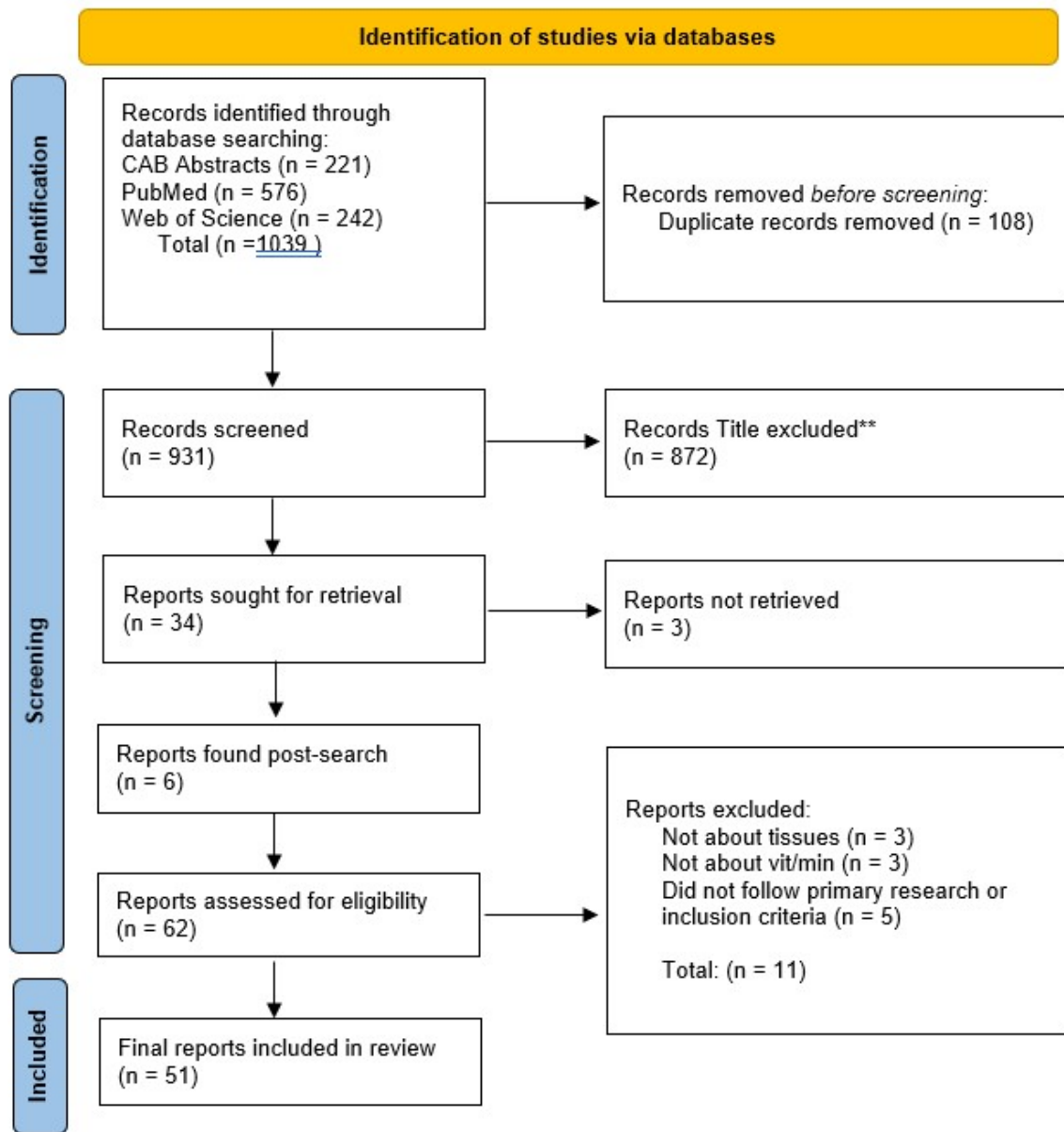


Figure 1.1. PRISMA flow diagram outlining the identification and inclusion of articles representing mineral and vitamin status within tissues of bison. Flow chart modified from the PRISMA 2020 Statement (Page et al., 2021)

3.2. Study Characteristics

This scoping review identified 51 studies investigating the American bison (*Bison bison*) and European bison (*Bison bonasus*). The studies originated from diverse geographic locations, with a concentration in Poland (n=26), particularly the Bialowieza Forest (n=24). The United States

(n=18) also contributed a notable portion of studies, with representation from various states such as South Dakota (n=7), Wyoming (n=5), and Michigan (n=5). Canada (n=8) was another source, with studies from Alberta (n=3) and other provinces. Figure 2 shows a distribution of study locations. Publication dates ranged from 1975 to 2023, with a trend of studies from Europe collecting data during the winter months due to opportunistic herd culling of European bison.

Sample sizes in studies were varied, ranging from 3 to 257 bison, with an average of approximately 72 animals per study. However, three studies that did not report final sample numbers and one study provided data on bison cuts instead of whole animals. The study population identified a near-equal split between studies on European bison (n=27) and American bison (n=25). This distribution mirrored the geographic spread, with European bison studies concentrated in Poland and Spain, and American bison studies in the US and Canada.

Management practices varied across studies. Seven studies investigated both free-range and captive bison, while 27 studies focused on only free-range bison and 16 focused on captive/privately owned bison. Two studies did not specify the management type. The age of bison within studies was also varied, with a reported range of less than 1 year to 25 years of age. Calves (under 1 year) were included in 12 studies, while studies on bison aged 1-3 years (n=38) and older than 3 years (n=21) were the majority of ages utilized. However, 12 studies lacked age data. Overall, the average bison age across studies was within 1-2 years of age.

Sex distribution within studies revealed a greater concentration focused on mixed-sex groups (n=32). Ten studies focused solely on bulls, while only one study investigated solely females. The sex of the bison was not reported in 9 studies.

The studies offered a variety of dietary information. The most common diet category was "woodlands" (n=26), encompassing elements like moss, coniferous trees, root vegetables, and supplemental hay. Additionally, studies documented full concentrate diets with minimal forage (n=13), rangeland grazing with minimal supplementation (n=15), and diets with unreported composition (n=2). One outlier study reported a mixed vegetable diet.

3.3. Measures

This scoping review identified key factors and their resulting effects on bison's mineral and vitamin status (both European and American). The factors considered (predictors) included species, animal characteristics, general nutrition, presence of diseases/conditions, and environmental impacts. The effects studied (outcomes) focused on the concentrations of vitamins and minerals in various bison tissues. These factors and effects were then organized into categories. Table 3 summarizes the specific predictor and outcome variables measured within each category. Notably, for the Tissue Type category, all specific tissues were grouped into broader categories. While the authors acknowledge that some individual tissues (like meat cuts) could belong to multiple categories, the classification in **Table 1.3** reflects the context and purpose of the original studies.

Table 1.3. Predictor and outcome categories from studies included in analysis (n = 51) for the scoping review

	Category	Variables Investigated
Predictors	Species	European bison (<i>Bison Bonasus</i>) or American bison (<i>Bison bison</i>)
	Animal Characteristics	Age and sex
	General Nutrition	Feedlot/confinement, rangeland, supplementation practices, and other feed management
	Presence of Diseases/Conditions	General health/conditions
	Environmental Impacts	Season, captive vs. free-ranging, location
Outcome	Tissue Type (Outcome Descriptives)	Blood, Liver, Kidney, Muscle, Bone, Hair, Hooves, Horns, Teeth
	Mineral Concentration	Aluminum (Al), Arsenic (As), Barium (Ba), Beryllium (Be), Calcium (Ca), Cadmium (Cd), Chlorine (Cl), Cobalt (Co), Chromium (Cr), Cesium (Cs), Copper (Cu), Florine (F), Iron (Fe), Mercury (Hg), Potassium (K), Lithium (Li), Magnesium (Mg), Manganese (Mn), Molybdenum (Mo), Sodium (Na), Nickel (Ni), Phosphorus (P), Lead (Pb), Sulfur (S), Antimony (Sb), Selenium (Se), Tin (Sn), Strontium (Sr), Titanium (Ti), Uranium (U), Vanadium (V), Zinc (Zn)
	Vitamin Concentrations	A,B,C,E

3.3.1. Predictors

After reviewing 51 studies, a total of 13 predictor variables were categorized into the following categories: species, animal characteristics, general nutrition, presence of diseases/conditions, and environmental impacts. A descriptive summary of predictors within each category of included studies was recorded and are displayed in **Figure 1.2**. Age (n=37) and sex (n=42) were the highly reported categories due to these factors contributing to mineral and/or vitamin baseline statuses. Studies also largely investigated diet or feed management (n=49) and their subsequent mineral and vitamin concentrations within tissues due to diet being highly correlated with mineral and vitamin metabolism. Diet and feed are also very connected with whether the animals were captive or free-range.

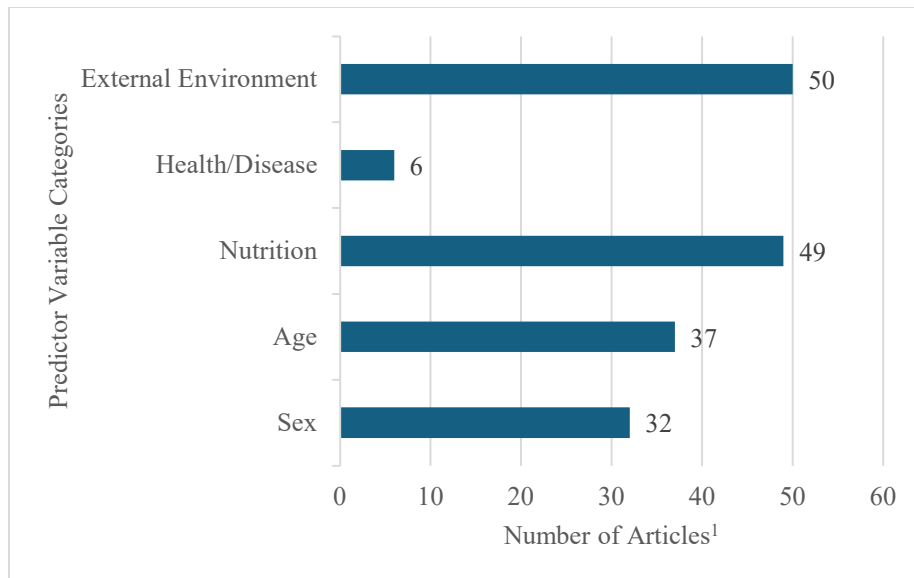


Figure 1.2. Number of studies per each predictor category comprised in the final scoping review analysis out of the total collection (n = 51).

¹Several studies conveyed multiple factors within each category, therefore the total number of variables reported in each category represent more than total studies contained in the analysis

3.3.2. Outcomes

After evaluating the 51 studies, 2 outcome variables were measured and categorized: mineral concentrations and vitamin concentrations. For this scoping review, the outcome interest was mineral and/or vitamin status of varying tissues (outcome descriptives) within bison (**Figure 1.3**), so each study should have studied at least one tissue with at least one vitamin or mineral concentration within the sample. Most studies investigated muscle (n=21) as the tissue type of interest, with blood following (n=21), liver (n=19), hair (n=14), kidney (n=12), hooves (n=8), bone (n=6), teeth (n=2), and horns (n=1) (**Figure 1.3**). The minerals most analyzed within the studies were Phosphorus (n=31), Calcium(n=25), Sodium (n=19), Potassium (n=16), and Magnesium (n=15). Uranium (n=1) , Antimony (n=1), Cesium (n=1), Thorium (n=1), Fluoride (n=1), Tin (n=2), Beryllium (n=2), Chromium (n=2), Nickel (n=2), Lithium (n=2), and Sulfur (n=2) were the least analyzed within the studies of interest (**Figure 1.4**).

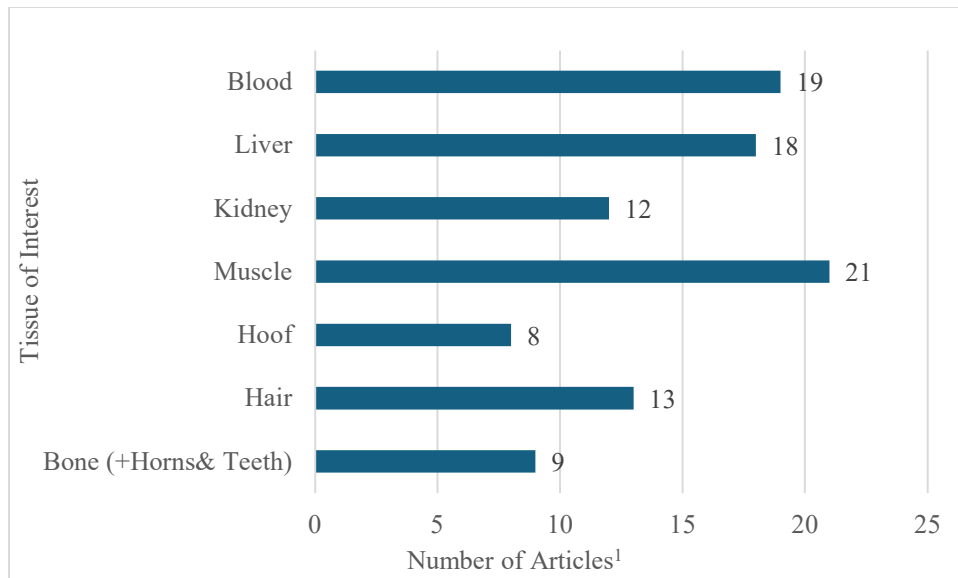


Figure 1.3. Number of studies per each outcome category of tissue of interest in the final scoping review analysis (n=51).

¹Several studies reported multiple outcomes within each category, therefore the total number of variables reported in each category represents more than total studies included in the analysis.

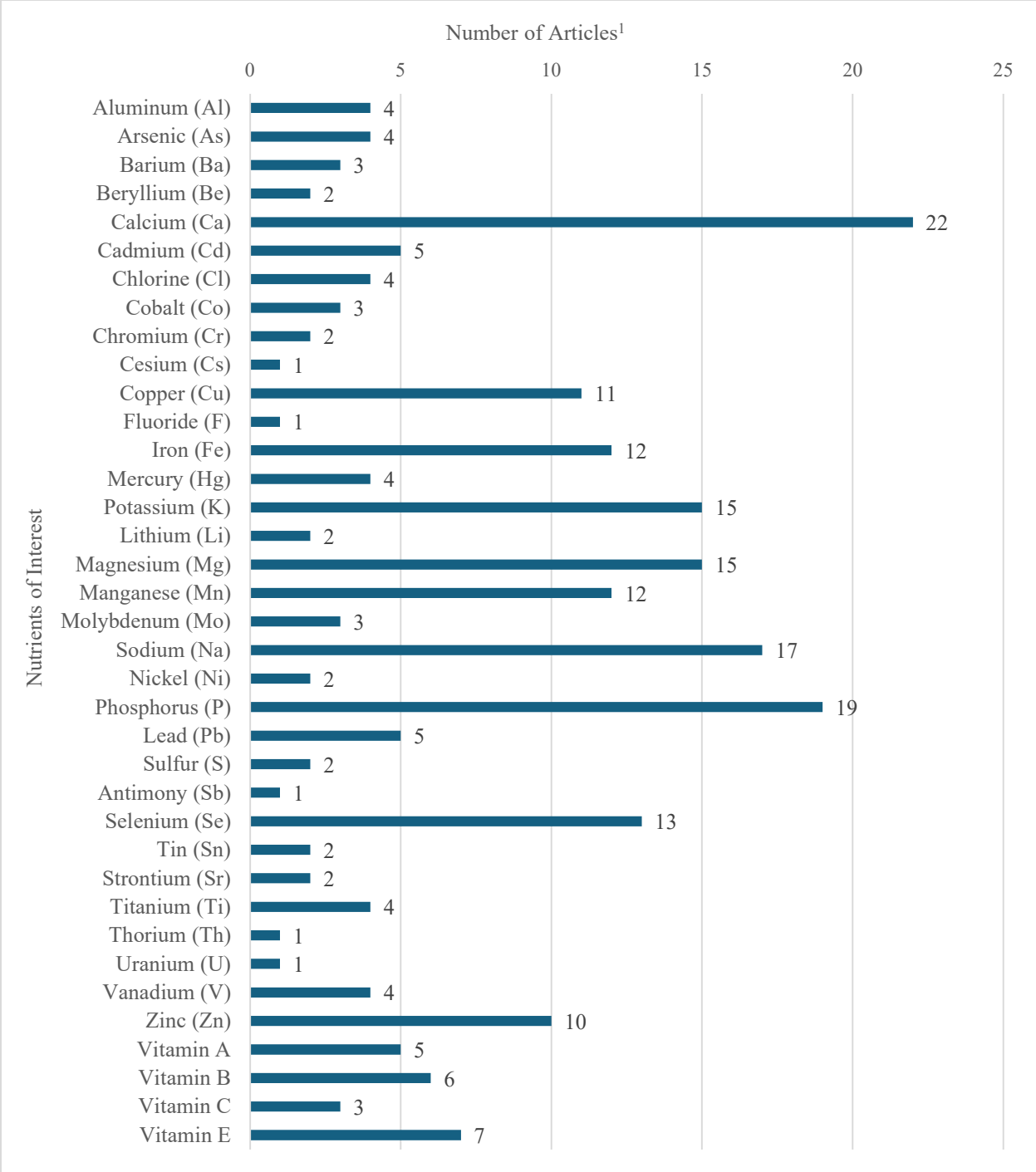


Figure 1.4. Number of studies per each outcome variable of nutrient of interest (mineral or vitamin) in the final scoping review analysis (n=51).

¹Several studies reported multiple outcomes within each category, therefore the total number of variables reported in each category represents more than total studies included in the analysis.

4. Discussion

4.1. Summary of Main Findings

4.1.1. Factors and Outcomes

The scoping review revealed that the majority of studies centered on the topics of nutrition and external environment (i.e. management practices) in bison populations (Debska et al., 2006a,b, Kosla et al., 2011, Marchello et al., 1998, Sikarskie et al., 1990). This focus is likely due to the well-established link between an individual's physiological status and its capacity for nutrient intake and forage utilization (Hawley and Peden, 1982). Effective management strategies often rely on understanding these nutritional dynamics, underscoring their importance in optimizing bison health, growth, and productivity (Kosla, 1993). Research related to sex and age was the next most studied area, frequently overlapping with investigations into nutrition and management (Kosla et al., 2010, Peinado et al., Vestweber et al., 1991). Such studies highlight the interconnectedness of these factors, as age and sex are known to influence nutritional requirements, growth rates, and reproductive behaviors in bison.

In contrast, health was identified as the least researched domain among the articles included in this review (Debska et al., 2005, Klich et al., 2021, Rhodes et al., 2018, Wolk and Krasinska, 2004). The limited focus on health-related factors may be attributable to the challenges associating health condition with bison mineral and vitamin status. These elements are critical to overall health but remain understudied, likely due to the complexities involved in measuring their bioavailability and interactions within the bison's unique physiology (Klich et al., 2021, Debska et al., 2005). This gap in the literature suggests that future research exploring health-related variables could provide valuable insights, particularly in the context of improving conservation and management practices.

4.1.2. Factor and Outcome Relationships

The remainder of the discussion section is structured to examine the outcomes of mineral and vitamin concentrations across different tissues and their associations with relevant predictors. Each section is organized by mineral or vitamin outcome and then is sub-sectioned by the main predictor of interest within the study. Within each mineral or vitamin category, tissue type outcomes are discussed in detail, emphasizing their relationships to the nutrient under investigation. Additionally, given that many studies included in this review rely on cattle reference ranges for comparative purposes, these comparisons are incorporated where applicable. This inclusion provides readers with contextual insights into potential similarities and differences between bison and cattle, offering a broader perspective on the findings.

4.2. Minerals

4.2.1. Calcium (Ca)

4.2.1.1. Sex

Notably, Ca levels in male and female bison did not significantly differ in many of the studies. For example, Zaugg et al. (1993) and Wołk and Józefczak (1988) both found no significant difference in serum Ca concentrations between males and females in American bison and European bison, respectively. Comparable results were observed by Wolk and Krasinska (2004) and Wolf et al. (2004), with no significant sex differences in healthy European bison Ca serum concentrations. Additionally, studies investigating Ca levels in various tissues such as liver, kidney, rib, and muscle also showed no significant differences between sexes (Kośła et al., 2010). However, more recent research by Klich et al. (2021, 2023) noted that males have tendency to have higher Ca concentrations in the liver compared to female. The authors hypothesize that it is possibly due to the increased Ca demand in females during lactation. These

variations underscore the complexity of Ca metabolism in bison and indicate that while sex may not always be a critical factor, certain physiological states, such as milk production, could influence Ca distribution in females. Interestingly, meat cuts from bulls and heifers in American bison showed differences in Ca content within individual cuts, but no overarching sex differences for similar cuts (Galbraith et al., 2006).

4.2.1.2. Age

Ca statuses across different ages of bison revealed varied findings, with most studies indicating no significant differences in Ca concentrations between age groups. For instance, Marler (1975) reported no significant difference in serum Ca levels between American bison under 2 years (11.0 mg/100ml) and those over 2 years (10.6 mg/100ml). Similarly, a study on European bison by Wolk and Krasinska (2004) found no significant age-based differences in ionized Ca concentrations across groups less than 1 year, 1-4 years, and over 4 years. However, there were some notable age-related patterns; Wolf et al. (2004) observed a difference in the Ca-to-K ratio between European bison calves (1.2) and adults (1.00). Vestweber et al. (1991) reported a significant decrease in serum Ca with advancing age in American bison from 6 months to 23 months. Kośła et al. (2010) found no significant difference in Ca levels across tissues (liver, kidney, rib, muscle, hair, hoof) between European bison under and over 1 year of age, except for muscle, where older bison had higher concentrations. Additionally, Dębska et al. (2006a) reported no significant Ca differences in hair, serum, liver, or kidney between European bison calves, youth, and adults. When authors also compared values to beef cattle values, hair Ca concentrations were notably lower than those of beef cattle references. Overall, these findings suggest that while Ca levels remain consistent across ages, specific physiological demands, such as growth or muscle development, may influence Ca distribution in certain tissues.

4.2.1.3. Nutrition

Studies investigating the relationship between nutrition and Ca statuses in bison focused on free-range animals. Marchello and Driskell (2001) found no significant difference in Ca content between grass- and grain-finished American bison meat, with Ca concentrations in meat ranging from 4.7 to 7.4 mg/100g across cuts like ribeye and top sirloin. Similarly, Marchello et al. (1989, 1998) reported Ca concentrations of 4.0-6.0 mg/100g in grain-fed American bison. Wolk and Krasinska (2004) speculated that low Ca levels in European bison during winter might be due to Ca-deficient hay in the Bialowieza forest, a key habitat for European bison in Poland. Dębska et al. (2006b) observed that captive European bison had higher serum (2.4 mmol/l) and hair (836 ppm) Ca concentrations compared to free-range counterparts (2.31 mmol/l serum, 575 ppm hair), indicating for the authors that natural forage might offer more bioavailable Ca. Kośła (1993) also noted lower serum Ca levels in European bison compared to cattle despite appropriate fodder content. Additionally, Keith et al. (1978) found no significant difference in serum Ca between American bison fed high- and low-energy/nitrogen diets. Overall, while nutrition plays a role in Ca levels, most studies found no significant difference between feeding types, though natural forage in free-range environments may enhance Ca bioavailability.

4.2.1.4. Health/Disease

Studies investigating the relationship between health conditions and Ca statuses in bison reveal few significant differences in Ca levels between healthy and afflicted animals, with balanoposthitis being one of the most researched diseases found in the review. For instance, Miller et al. (1989) found no significant difference in serum Ca levels (9.9 mg/dl) in American bison compared to the cattle average reported in the study, and no variation between treatment groups for tuberculosis. Similarly, Wolk and Krasinska (2004) reported no significant difference

in Ca concentrations (mmol/l) between posthitis-affected European bison males and healthy counterparts. Wolf et al. (2004) also found no significant Ca disparity between healthy European bison males and those with balanoposthitis. Dębska et al. (2005) noted that while Ca levels in bison with balanoposthitis were lower than cattle reference values, the difference between healthy and affected bison was not statistically significant. Investigating other diseases, Marczuk et al. (2015) found no significant difference in serum Ca levels in European bison with chronic liver flukes compared to unaffected animals. Moreover, liver Ca concentrations showed no significant associations with comorbidities in European bison (Klich et al., 2023). Overall, the research suggests that disease conditions such as balanoposthitis or chronic liver flukes do not significantly impact Ca levels in bison, with most findings showing minor variation between healthy and diseased individuals.

4.2.1.5. External Environment

Research on captive animals (versus free-range animals) shows that environmental conditions studied often do not result in significant differences in Ca levels. For example, Sikarskie et al. (1990) found no significant difference in serum Ca concentrations between captive and free-range American bison, with values of 9.68 mg/dl and 9.69 mg/dl, respectively. However, some site-specific variations in European bison populations have been observed. Klich et al. (2021) reported that European bison living in the Bieszczady Mountains had higher liver Ca concentrations as compared to a variety of other sites in Poland, authors speculate this is potentially due to elevated Ca levels in mountainous water sources. Additionally, Dębska et al. (2006b) found higher serum (2.4 mmol/l) and hair (836 ppm) Ca levels in captive European bison compared to free-range animals (2.31 mmol/l serum, 575 ppm hair), though all values were below reference levels for cattle. Geographic differences between American bison populations

were also noted by Brzuski et al. (2010), who found lower serum Ca levels in Polish American bison compared to U.S. American bison, possibly due to limited pastureland variability or insufficient dietary supplementation in Poland. These findings suggest that while management and geo-location may influence Ca levels in bison, the differences are often subtle and may depend on specific and compounding environmental factors such as water mineral content, seasonality, and/or nutrition of available feedstuffs.

4.2.2. Phosphorus (P)

4.2.2.1. Sex

Research consistently demonstrates minimal or no significant variation in P concentrations between male and female animals. For instance, Zaugg et al. (1993) reported higher serum P concentrations in bulls (8.38 mg/dl) compared to cows (5.5 mg/dl) in American bison. However, this difference was attributed to factors like stress from euthanasia and extended serum clotting times, rather than sex. Similarly, in European bison, Wołk and Józefczak (1988) found no significant sex-based differences, with P levels of 4.89 mg/dl in males and 5.54 mg/dl in females. Further support comes from Wolf et al. (2004), who observed no significant sex-related variation in European bison serum P concentrations. Witkowska and Kotik (1987) also found no significant differences in P concentrations (Pi and Pt) in longissimus muscle tissues between sexes of European bison. Finally, Kosla et al. (2011) reported no significant sex-related differences in hair P concentrations in free-ranging European bison, with males at 257.75 mg/kg and females at 237.93 mg/kg. These findings collectively suggest that sex does not play a key role in influencing P concentrations across tissues and species, with any observed differences likely attributable to external factors rather than intrinsic sex differences.

4.2.2.2. *Age*

Phosphorous concentrations appear to be strongly influenced by age across several studies within this review, mostly attributed to the physiological demands associated with growth and development. Younger animals consistently had higher P concentrations, likely due to the increased need for P during periods of rapid bone growth and metabolic activity. For instance, Zaugg et al. (1993) reported higher serum P levels in calves (9.62 mg/dl) compared to bulls (8.38 mg/dl) and cows (5.5 mg/dl), although the study attributed some variability to external factors like stress and serum clotting times. Similarly, Wołk and Józefczak (1988) observed that P levels decreased with age in European bison, with younger animals under two years old having higher inorganic P concentrations (3.5 mg/dl) than adults (2.8 mg/dl), a pattern echoed by Vestweber et al. (1991) in American bison, where P levels significantly declined as age increased. Despite this trend, some studies found no significant age-related differences in P concentrations. Wolf et al. (2004) and Peinado et al. (1999) both reported no significant variation in serum P between calves and adult bison in their respective studies. However, age differences in muscle P concentrations were observed in Witkowska and Kotik's (1987) study, where younger European bison showed higher P content in Longissimus dorsi muscle. A more complex picture emerged in Dębska et al. (2006a), who found a significant decrease in European bison serum, hair, and kidney P concentrations with age, but no age-related difference in liver P. Overall, these studies suggest that while P concentrations generally decrease with age, reflecting reduced metabolic demand and absorption efficiency, the effect of age may vary depending on the specific tissue analyzed and the environmental or physiological conditions of the animals.

4.2.2.3. *Nutrition*

Phosphorus concentrations in bison are notably influenced by diet composition, muscle cuts, and feeding regimens. In a study, Dębska et al. (2006b) reported that captive European bison fed supplemented diets had a serum inorganic P concentration of 2.30 mmol/l, and hair P was 154 ppm, while grass-fed European bison had 2.47 mmol/l in serum and 136 ppm in hair. Hawley and Peden (1982) further noted that in American bison, P concentrations in serum increased with higher crude protein content in the diet and decreased with higher dietary energy levels, with bison consistently having higher serum P levels than cattle. Similarly, no significant difference of serum from fistulated American bison with high and low energy/nitrogen diets was discovered (Keith et al., 1978). These findings emphasize the complex relationship between diet, P intake, and resulting P concentrations in different tissues and cuts of bison, highlighting the role of nutrition in P metabolism.

When analyzing different meat cuts of bison on their nutritional values of P, Marchello and Driskell (2001) found that in grass-finished American bison, P levels varied among cuts, with the Top Sirloin containing 189 mg/100g wet weight and Top Round at 185 mg/100g, both significantly higher than the Ribeye, which had 171 mg/100g. In a comparison between bison and beef, Marchello et al. (1989) reported that American bison longissimus muscle had higher P concentrations at 187 mg/100g, compared to beef at 172 mg/100g, indicating that bison meat generally contains more P than beef. Further, Marchello et al. (1998) investigated American bison fed concentrate diets, finding P concentrations of 198 mg/100g in Ribeye, 203 mg/100g in Sirloin, 204 mg/100g in Top Round, and 189 mg/100g in Clod, with significant differences among these cuts. Kośła (1993), studying European bison, found that P intake and microelement

concentrations revealed hair P content of 160 mg/kg dry matter, while serum inorganic P was 1.79 mmol/l, both values within the recommended ranges for ruminants.

4.2.2.4. Health/Disease

The effect of health and disease on P concentrations in bison appears to be minimal according to several studies within this review. Wolf et al. (2004) found no significant difference in serum P levels between healthy European bison and those diagnosed with balanoposthitis, indicating that this condition does not markedly affect P status. Similarly, Miller et al. (1989) investigated P concentrations in American bison infected with *Mycobacterium bovis* and found no significant difference in serum P levels between healthy and infected animals. The P concentrations in these bison fell within the reference ranges for cattle, which are 4.4-11.5 mg/dl for bison and 5.6-8.0 mg/dl for cattle, indicating that tuberculosis did not significantly alter P levels in that study. In a comparison of serum P levels among domestic ruminants and free-range European bison with liver flukes, Marczuk et al. (2015) reported no significant differences in P concentrations, with a mean serum P level of 3.45 mmol/l for infected bison. Similarly, Dębska et al. (2005) compared European bison with and without balanoposthitis and found only a slight difference in inorganic P concentrations, with infected bison at 2.68 mmol/l and healthy bison at 2.48 mmol/l. Both values were within the reference ranges for cattle (1.0-2.71 mmol/l), reinforcing that common diseases do not significantly disrupt P homeostasis in bison. These findings collectively suggest that while certain health conditions may influence P metabolism, the variations are generally within the physiological range and do not reflect dramatic changes in P concentration.

4.2.2.5. External Environment

Phosphorus concentrations in bison are significantly influenced by environmental factors, geographical location, and management practices. Witkowska and Kotik (1987) found that P concentrations in muscle tissue varied due to external conditions such as time, year, and severity of environmental factors, suggesting that these variables play a critical role beyond just dietary influences. Sikarskie et al. (1990) observed a notable difference in serum P levels between captive and free-range American bison, with captive bison showing an average concentration of 6.5 mg/dl compared to 4.37 mg/dl in free-range bison. The authors attribute this difference is likely due to variations in protein intake and highlights how management practices and nutrition can impact P status. Furthermore, Hawley and Peden (1982) reported that serum P levels in juvenile bison from Wood Buffalo National Park were significantly higher in deceased individuals, averaging 7.525 mg/dl, compared to live juveniles. Although the bison sampled were from the same geographic location, this study highlights the importance of the timing of collection, as it can significantly impact serum P concentrations. These findings collectively underscore the complex interactions between environmental conditions, geographical location, and management practices in influencing P metabolism in bison.

4.2.3. Sodium (Na)

4.2.3.1. Sex

Multiple studies present varying results across different animal populations when investigating the effects of Na concentrations based on sex. Zaugg et al. (1993) found no significant differences in serum Na concentrations between male and female American bison in the Yellowstone herd, with cows averaging 142.52 mEq/L and bulls 137.50 mEq/L. Similarly, Wolk and Krasinska (2004) reported no significant sex differences in serum Na concentrations

among European bison from Bialowieza Forest, with males averaging 133.27 mmol/L and females 144.04 mmol/L. Kosla et al. (2015) also observed no significant sex differences in tissue Na concentrations in European bison, despite differences in Na content across tissues such as liver, kidney, and muscle. The study did, however, find correlations between Na and K levels in various organs, indicating complex interactions between these electrolytes. In contrast, Galbraith et al. (2006) identified significant differences in Na concentrations across different cuts of American bison meat, with bulls showing notably higher Na levels in the bottom round and heifers in the clod and sirloin. Durkalec et al. (2018) further demonstrated significant sex differences in European bison liver Na concentrations, with females exhibiting a wider range of Na levels than males. These findings suggest that while sex may not always play a significant role in Na concentrations, certain contexts, such as tissue type or differing meat cuts, may reveal differences between observed concentrations.

4.2.3.2. Age

The impact of age on Na concentrations in bison is variable across the different studies and tissues. Several studies report no significant age-related differences in serum Na concentrations. For example, Wolk and Krasinska (2004) found no significant difference in European bison Na levels between younger animals (1–4 years, 141.73 mmol/L) and those older than four years (144.99 mmol/L), while Sikarskie et al. (1990) similarly observed no difference in captive American bison, with calves averaging 145.2 mmol/L and adults 144.80 mmol/L. Peinado et al. (1999) also found no significant difference between adult and young European bison serum Na concentrations. However, some studies suggest that Na concentrations can vary with age in specific contexts. Vestweber et al. (1991) reported significantly higher Na levels in American bison calves (154.14 mmol/L) compared to those aged 7–23 months (149.54 mmol/L)

and older bison (151.30 mmol/L), suggesting that younger bison may retain more Na. Similarly, Kosla et al. (2015) found significant differences in Na concentrations in hair between calves and adults, although other tissues like liver and kidney showed no significant variation. Dębska et al. (2006a) also identified significant differences in kidney Na concentrations across age groups in European bison, with calves exhibiting lower levels than adults. These findings suggest that while age may not significantly influence Na concentrations in serum, certain tissues, such as hair and kidneys, may exhibit age-related differences, particularly in younger animals.

4.2.3.3. Nutrition

The effect of nutrition on Na concentrations in bison differs depending on the specific tissues and dietary conditions studied. Marchello and Driskell (2001) found no significant differences in Na levels between grass-fed and grain-fed American bison in raw separable lean cuts. However, they did observe significant differences in Na content across various cuts of meat, with the ribeye (44.9 mg/100 g) and clod (47.7 mg/100 g) showing significantly higher Na levels compared to the top round (39.7 mg/100 g). Despite these variations, the differences are unlikely to affect human dietary Na intake recommendations. Conversely, studies focusing on diet and serum Na concentrations showed little impact of nutrition. Keith et al. (1978) reported no significant difference in serum Na concentrations between American bison fed high- and low-energy/nitrogen diets, suggesting that dietary variations in energy and nitrogen do not strongly influence Na levels in the serum. However, Kośła (1993) found that European bison feeding on forage low in Na had relatively high Na concentrations in their hair (618.0 mg/kg), indicating that dietary supplementation, such as hay, likely helped compensate for low natural Na intake. Dębska et al. (2006b) further observed that European bison had lower Na levels in both free-range and captive diets than recommended by NRC guidelines, yet hair Na concentrations were

significantly higher in captive animals (252.0 ppm) compared to free-range ones (96.0 ppm), suggesting better Na intake in captivity. Differences in Na content across tissues, particularly in hair and certain cuts of meat, highlight the role that diet may play in specific contexts, such as mineral access or in response to dietary supplementation. When analyzing general meat Na concentration, Marchello et al. (1998) found that Na varied significantly across cuts of concentrate-fed American bison, with ribeye and clod cuts showing the highest Na levels, while no significant differences were found between sirloin and top round. Overall, while Na concentrations in bison muscle and hair vary based on nutrition and diet, the effect of nutrition on serum Na levels appears limited.

4.2.3.4. Health/Disease

The impact of Na on the health of bison, particularly European bison, appears to be minimal in terms of mineral deficiencies and overall health status based on current available literature. Durkalec et al. (2018) investigated Na deficiencies in European bison and found no significant differences in liver Na levels between captive and free-ranging animals, with concentrations remaining above the standard reference of 800 mg/kg wet weight. This suggests that Na deficiency is not a common health issue in either population. Additionally, Dębska et al. (2005) analyzed serum Na concentrations in European bison and found levels to be within the healthy range based on cattle reference standards, with no significant differences between healthy animals (138.81 mmol/L) and those diagnosed with balanoposthitis (139.67 mmol/L). These findings indicate that Na concentrations in both liver and serum are generally adequate and stable, regardless of health conditions or captivity status, suggesting that Na imbalances are not a significant factor in bison health.

4.2.3.5. External Environment

Sodium concentrations in bison appear to be minimally affected by environmental factors such as geologic location and general management practices, with most studies reporting no significant differences across various conditions. Sikarskie et al. (1990) found no significant difference in serum Na concentrations between free-range and captive American bison in South Dakota and Michigan, with captive bison averaging 145 mmol/L and free-range bison 146.3 mmol/L. Similarly, Marchello et al. (1989) reported no significant differences in Na content between American bison and beef in the longissimus muscle or across different cuts of bison meat, with Na levels remaining consistent across samples. However, variations in Na concentrations by geologic location were observed in European bison. Klich et al. (2021) found that Na concentrations in European bison varied by site location in Poland, with bison from Knysynska Forest exhibiting lower Na levels than those from Bialowieska, Borecka, and Bieszczady regions. This suggests that local environmental factors, such as soil composition or forage quality, might influence Na availability in certain areas. Despite this, Klich et al. (2023) found no significant difference in liver Na concentrations between bison from enclosed and free-range environments or between different sites (Bialowieza and Smardzewice), indicating that enclosure or geographic site might not strongly impact internal Na levels in European bison. Overall, Na concentrations in bison are relatively stable across management systems, though some regional variations may occur due to local environmental conditions.

4.2.4. Potassium (K)

4.2.4.1. Sex

Potassium statuses in bison across different sexes highlighted some differences, although stress-related factors may play a role in these variations. Zaugg et al. (1993) examined free-

ranging American bison in Yellowstone and found that bulls had significantly higher serum K concentrations (14.42 meq/L) compared to cows (11.70 meq/L). These K levels were notably higher than those reported in other bison studies, which the researchers attributed to the momentary stress caused by the gunshot wound to the head and the time taken to collect blood samples. This elevated K level due to stress suggests that acute stressors may temporarily affect serum K concentrations, making it difficult to determine whether the differences between sexes are physiological or situational. However, Klich et al. (2021) analyzed liver concentrations of K and found that female European bison had statistically higher concentrations than males. Overall, while there are observed differences in K levels between male and female bison, the impact of external factors, such as stress during sampling, must be considered when interpreting these findings. Further studies controlling for such stressors would be needed to better understand the inherent sex-related differences in K statuses in bison.

4.2.4.2. Age

In free-ranging Yellowstone American bison, Zaugg et al. (1993) reported serum K concentrations in adults ranging from 5.8 to 31.5 mEq/L and in calves from 8.1 to 19.4 mEq/L. Similarly, Sikarskie et al. (1990) found no significant difference in serum K between captive American bison adults (4.72 mEq/L) and calves (5.19 mEq/L). Likewise, Vestweber et al. (1991) observed only minor fluctuations in American bison K levels based on age, with no significant differences, reporting values of 5.88 mmol/L for calves and 5.54 mmol/L for adults. For European bison in the Bialowieza Forest, Wolk and Krasinska (2004) reported a significant age-related decline in serum K, with <1-year-old bison at 9.42 mmol/L, 1-4 years at 8.65 mmol/L, and adults over 4 years at 7.68 mmol/L, all significantly higher than in previous years' data. Kośła et al. (2015) also found age-dependent differences in K levels in tissues, with significant

variations in rib K between younger and older European bison, though other tissues like liver and kidney showed minor differences. Additionally, Dębska et al. (2006a) noted K concentrations in calves, youth, and adults were consistent across tissues but with lower hair K compared to cattle reference data. Finally, Klich et al. (2021) highlighted site- and sex-based variations in K levels, with female European bison exhibiting higher K, likely due to milk production demands. Overall, while some studies observed age-related K changes, particularly in European bison, many showed no significant differences between age groups, with variations often linked to specific environmental or physiological factors.

4.2.4.3. Nutrition

Only one study within the review investigated the effects of nutrition on K statuses in bison; the study highlighted how dietary energy levels and seasonal factors can influence K concentrations. In a study by Keith et al. (1978), two groups of American bison in Colorado were fed either a high-energy or low-energy diet and compared for serum K concentrations. It was found that bison on the high-energy diet had serum K levels ranging from 5.2 to 4.2 mEq/L, while those on the low-energy diet had slightly lower K levels, ranging from 4.6 to 4.4 mEq/L. Interestingly, the study also noted a seasonal variation in K levels, with bison on high-energy diets exhibiting higher serum K concentrations during the winter compared to spring and summer. This suggests that dietary energy intake, along with environmental conditions, plays a role in regulating K levels in bison; however, the limited research on K and its relationship with nutrition warrants further investigation.

4.2.4.4. Health/Disease

Studies investigating the relationship between health conditions and K statuses in bison suggest that certain diseases may not significantly affect serum K concentrations, although elevated levels have been observed in some cases. For European bison, Wolk and Krasinska (2004) found no significant difference in serum K levels between males diagnosed with balanoposthitis (9.02 mmol/l) and healthy individuals (8.38 mmol/l). However, the study noted that elevated K levels, or hyperkalemia, can be associated with various health issues such as kidney disorders, pneumonia, pleurisy, and acute pancreatitis. Among the examined animals, kidney cysts were present in 18 out of 102 bison, and many were diagnosed with pulmonary helminthiasis, pneumonia, or bronchitis, often due to parasitic infections. Similarly, Dębska et al. (2005) found no significant difference in K levels between balanoposthitis-positive bison (8.22 mmol/l) and healthy individuals (7.99 mmol/l), although both groups had higher K concentrations than cattle reference values. These findings suggest that while health/disease may not always result in significant changes in K levels in bison, underlying health conditions such as kidney and respiratory issues could potentially influence K metabolism. Further research is needed to fully understand the role of K in disease pathology in bison.

4.2.4.5. External Environment

Studies investigating the effects of environmental and management conditions on K statuses in bison reveal notable differences between free-range and captive populations, as well as between various geographic regions. Klich et al. (2021) found that K concentrations in European bison varied based on their origin, with serum K levels differing significantly across most regions in Poland, except for those from the Knysynska and Bialowieska forests where no significant differences were observed. Management conditions also play a role, as Dębska et al.

(2006b) found that captive European bison had significantly higher serum (8.54 mmol/L) and hair K concentrations (588 ppm) compared to free-range bison (serum: 8.09 mmol/L, hair: 278 ppm). The higher K levels in captive bison were likely due to supplemented feed, which provided more available K than the natural forage consumed by free-range animals. In contrast, free-ranging bison had lower K intake, potentially contributing to higher Mg levels in their serum. Similar differences were observed in American bison, where Sikarskie et al. (1990) reported higher serum K levels in free-range AB from South Dakota (5.57 mEq/L) compared to captive American bison in Michigan (4.95 mEq/L). These findings suggest that both geographic origin and management practices significantly influence K levels in bison, with captive animals generally having higher K due to controlled diets, while free-range animals may experience greater variation depending on environmental factors.

4.2.5. Magnesium (Mg)

4.2.5.1. Sex

Studies investigating Mg statuses in bison across different sexes generally show minimal significant differences between males and females. In free-ranging European bison from the Bialowieza Forest, Kośła et al. (2011) found no significant difference in Mg concentrations in hair, with males at 107.17 mg/kg and females at 92.77 mg/kg. Similarly, Durkalec et al. (2018) reported no significant sex-based difference in hepatic Mg concentrations, with females ranging from 104.04 to 184.19 mg/kg and males from 92.42 to 172.72 mg/kg. Although no direct link was found between sex and Mg concentrations in the liver, the study did note positive relationships between Co and Mg, as well as negative correlations between Mg and Na. However, Klich et al. (2023) observed that females consistently had lower hepatic concentrations of several elements, including Mg, compared to males, though the differences were not

statistically significant for Mg alone. Furthermore, Klich et al. (2021) found no correlation between Mg and other studied factors, such as sex or environmental conditions, in their examination of hepatic trace elements. Overall, while there are some observed trends of lower Mg levels in female Bison, the differences are generally not significant, and Mg appears to be consistent across sexes in both hair and liver tissues.

4.2.5.2. Age

The effects of age on Mg statuses in bison show varied results across different tissues and age groups, with significant differences observed in some tissues but not others. For American bison, Sikarskie et al. (1990) found no significant difference in serum Mg concentrations between calves (2.72 mg/dl) and adults (2.60 mg/dl). However, in European bison, Kośła et al. (2012) reported significant age-related differences in both hair and hoof Mg concentrations, with calves showing higher Mg levels in hair (107 mg/kg) and hoof (156 mg/kg) compared to adults (69.4 mg/kg in hair, 110 mg/kg in hoof), while other tissues like muscle, liver, and kidney showed no significant variations. Similarly, Dębska et al. (2006a) found significant differences in Mg levels in serum, hair, and liver across age groups, with calves showing higher serum Mg (0.99 mmol/l), hair Mg (80.08 ppm), and liver Mg (205.60 ppm) compared to adults, whose levels were lower in all three tissues. However, no significant differences were observed in kidney Mg concentrations across ages. In contrast, Kośła et al. (2011) found no significant age-related differences in Mg concentrations in hair among free-ranging European bison. Furthermore, Klich et al. (2021) observed no correlation between Mg and age or other factors in hepatic Mg concentrations. Overall, while some tissues, particularly hair and liver, exhibit significant age-related differences in Mg concentrations, others, like serum and kidney, show

minimal variation, indicating that Mg distribution may vary with age depending on the tissue type.

4.2.5.3. Nutrition

Research analyzing the effects of nutrition on Mg statuses in bison reveals both subtle differences based on diet type and significant variations across different meat cuts. Marchello and Driskell (2001) found that grass-finished American bison had slightly higher Mg concentrations (25.8 mg/100g) compared to grain-finished bison (24.2 mg/100g). Among grass-finished bison cuts, the ribeye had significantly lower Mg levels (24.3 mg/100g) compared to the top sirloin (27.0 mg/100g) and top round (26.5 mg/100g). In European bison, Kośła (1993) analyzed the Mg content of the diet, including grasses, forbs, and supplemented hay, and found it inadequate for the herd's nutritional needs based on cattle and bison references. Although European bison serum Mg levels (0.78 mmol/l) fell within cattle reference ranges, hair Mg concentrations (186 mg/kg D.M.) were lower than those of black and brown cattle. Furthermore, Dębska et al. (2006b) observed that free-range European bison had higher serum Mg levels than captive bison, suggesting that natural forage might better meet Mg requirements than supplemented diets, especially as high potassium (K) in captive diets may negatively correlate with Mg absorption.

When investigating meat concentrations of Mg, Marchello et al. (1998) reported differences among grain-fed American bison cuts, with clod showing significantly lower Mg concentrations (23.3 mg/100g) than ribeye (24.1 mg/100g), top sirloin (24.5 mg/100g), and top round (24.8 mg/100g). Overall, while nutritional conditions influence Mg levels in Bison, variations in dietary sources, such as natural forage versus supplemented feed, play a key role in determining Mg sufficiency.

4.2.5.4. Health/Disease

Mg statuses in bison show no significant differences in Mg concentrations between healthy and diseased individuals. In European bison euthanized in Poland due to clinical signs of illness, Klich et al. (2023) found no significant difference in hepatic Mg concentrations between individuals with observed clinical signs or comorbidities. This suggests that in these instances illness did not substantially affect Mg storage in the liver. Similarly, Dębska et al. (2005) reported no significant difference in serum Mg levels between healthy European bison (0.96 mmol/l) and those diagnosed with balanoposthitis (0.95 mmol/l), with both values falling within cattle reference ranges. These findings indicate that Mg concentrations in both the liver and serum remain stable regardless of disease presence, highlighting that Mg status is not a reliable biomarker for diagnosing or assessing health conditions in bison. The stability of Mg levels across different health statuses suggests that other elements or factors may be more sensitive indicators of disease in bison populations.

4.2.5.5. External Environment

Sikarskie et al. (1990) found no significant difference in serum Mg concentrations between captive American bison in Michigan (2.67 mg/dl) and free-range AB in South Dakota (2.79 mg/dl). Similarly, Durkalec et al. (2018) reported no significant difference in liver Mg concentrations in European bison based on management style, with captive herds having Mg levels of 92.42–184.19 mg/kg and free-ranging herds showing levels of 96.82–169.72 mg/kg. However, Dębska et al. (2006b) found a statistically significant difference in serum Mg levels between captive (0.89 mmol/l) and free-ranging EB (0.99 mmol/l), although hair Mg concentrations showed no significant variation between management types. In terms of site differences, Durkalec et al. (2018) noted no significant variation in liver Mg concentrations

between European bison populations in different regions, such as Bialowieza and Smardzewice. Marczuk et al. (2015) also observed that European bison had significantly higher serum Mg concentrations (1.33 mmol/l) than dairy cattle in the same region, but no difference compared to sheep, with the presence of liver flukes having no effect on Mg levels. Lastly, Marchello et al. (1989) found that American bison had significantly higher Mg concentrations in lean muscle (25 mg/100g) compared to beef cattle (23 mg/100g). Overall, while management and geographic factors show minimal effects on Mg levels, captive European bison tend to have lower serum Mg compared to their free-ranging counterparts.

4.2.6. Selenium (Se)

4.2.6.1. Sex

Studies investigating Se statuses in bison across different sexes indicate minimal differences between males and females in Se concentrations across various tissues. In American bison, Medeiros et al. (1993) found no significant interaction between sex and Se concentrations in muscle samples, although there were species-specific differences and interactions based on soil Se levels. European bison research by Kośła et al. (2019) also revealed no significant sex-based differences in Se concentrations, with male and female hair Se levels being 0.140 µg/g and 0.134 µg/g dry weight, respectively. Similarly, Se concentrations in the liver (0.175 µg/g wet weight) and kidneys (1.004 µg/g wet weight) showed no sex-related variation. Durkalec et al. (2018) further confirmed this, reporting no significant differences in liver Se concentrations between females (0.003-0.113 mg/kg wet weight) and males (<0.0011-0.073 mg/kg wet weight). Overall, these findings suggest that Se distribution in bison, whether in muscle, liver, kidney, or hair, does not significantly differ by sex, highlighting that Se metabolism is likely more influenced by environmental factors, such as soil Se content, rather than sex.

4.2.6.2. Age

Among the studies studying Se statuses in bison, only one paper addressed age differences. Kośła et al. (2019) found that Se concentrations in the hair of European bison (EB) were slightly higher in calves (up to 1 year of age) at 0.142 µg/g dry weight (DW) compared to individuals over 2 years of age, who had concentrations of 0.126 µg/g DW. However, the difference was not statistically significant, indicating that in that study age did not substantially influence Se levels in hair. Similarly, Se levels in the kidneys were within reference ranges for cattle but lower than those reported for free-range and experimental animals, suggesting that the bison population studied may have been Se deficient. This paper highlights that while sex is often explored in Se research, age-related differences are less frequently studied, with this study suggesting no major impact of age on Se concentrations in bison. Overall, the limited focus on age in existing literature suggests a need for further research to understand how Se statuses may vary across different life stages of bison.

4.2.6.3. Nutrition

Selenium statuses in bison across different diets reveal notable findings about Se concentrations in muscle tissues, largely influenced by regional soil Se levels and feeding practices. Medeiros et al. (1993) found that American bison had significantly higher Se concentrations in muscle samples (0.49 µg/g wet weight) compared to cattle (0.10 µg/g), with the high Se content linked to forage grown on Se-rich soils. This raised concerns about potential Se toxicity if bison meat from high-Se regions is consumed frequently. Driskell et al. (1997) explored Se concentrations in various bison muscle cuts (clod: 26.356 µg/g, ribeye: 23.238 µg/g, top round: 27.204 µg/g, top sirloin: 25.059 µg/g) and found that individual bulls had varying Se levels, with bulls from Se-rich areas like North Dakota showing higher Se concentrations, while

one bull fed a high vitamin E supplement exhibited lower Se levels due to negative correlations between vitamin E and Se. This study emphasized that bison meat, especially from Se-rich areas, could serve as a rich source of Se.

Research by Marchello et al. (1998) found no significant Se differences between bison cuts fed concentrate diets. However, Driskell et al. (2004) reported no significant difference in Se levels between grain-finished and grass-finished American bison bulls, though Se concentrations in ribeye were slightly higher in grain-finished animals. Marchello and Driskell (2001) noted that grass-finished bison had four times greater Se content in their meat (105.3 $\mu\text{g}/100\text{g}$) compared to grain-finished bison (25.5 $\mu\text{g}/100\text{g}$), highlighting that Se content in bison meat is largely dependent on dietary sources, such as grass versus grain.

4.2.6.4. Health/Disease

Schillhorn van Veen et al. (1991) reported that American bison from Michigan, some of which died from suspected organophosphate poisoning, had liver Se concentrations lower than cattle reference ranges (0.034-0.035 $\mu\text{g}/\text{g}$ dry weight). One bison showed mild fatty infiltration in the liver and brain lesions, while others displayed no significant pathophysiological changes. Similarly, Rhodes et al. (2018) found elevated Se levels (3.7 ppm) in the liver of euthanized American bison, with concurrent Cu deficiency likely contributing to increased Se absorption, further suggesting that mineral imbalances can exacerbate health issues. In European bison, Klich et al. (2023) identified that liver Se concentrations were significantly higher in bison with more numerous comorbidities, such as lung pneumonia. Despite the increased Se levels, these animals still showed overall Se deficiency based on cattle reference values, which, along with Cu deficiency, likely contributed to their deteriorating health. Additionally, Dębska et al. (2005) found no significant difference in serum Se levels between European bison with balanoposthitis

(0.32 $\mu\text{mol/l}$) and healthy individuals (0.25 $\mu\text{mol/l}$), though both values were lower than cattle references. The findings highlight the critical role of Se and other trace minerals like Cu in maintaining bison health, with deficiencies potentially leading to severe health consequences.

4.2.6.5. External Environment

Selenium statuses in bison across different environmental and management conditions highlight significant variations depending on geographic location and management practices. Sikarskie et al. (1990) found that American Bison from South Dakota had significantly higher serum Se concentrations (0.099 ppm) compared to those from Michigan (0.026 ppm), despite the Michigan bison receiving Se supplements and injections. Similarly, MacNeil et al. (1990) reported that American bison from Wood Buffalo National Park had deficient liver Se concentrations (0.11 ppm) and marginal kidney Se levels (0.58 ppm), while captive bison had Se levels within normal cattle reference ranges, with liver (0.65 ppm) and kidney (1.27 ppm) Se concentrations deemed adequate. In European bison, Klich et al. (2021) found that animals from the Bieszczady region in Poland had significantly higher liver Se concentrations compared to other sites, likely due to higher soil Se levels or better forage uptake. They also observed a strong correlation between Se and Cd concentrations, with Se potentially mitigating Cd toxicity through sequestration into inert complexes. However, other studies, such as Durkalec et al. (2018), noted no significant differences in liver Se concentrations between European bison from different sites, such as Bialowieza and Smardzewice, or between enclosed and free-range bison, though all animals sampled were found to be Se deficient based on previous literature. Additionally, Clemens et al. (1987) found that captive American bison had serum Se levels (0.30 ppm) similar to white-tailed deer but not pronghorn antelope in the same captivity. Overall, these studies suggest that environmental factors like soil Se content and management practices significantly

influence Se statuses in bison, with many populations showing deficiencies despite supplementation efforts.

4.2.7. Manganese (Mn)

4.2.7.1. Sex

Studies examining Mn statuses in bison across different sexes generally show minimal significant differences between males and females in Mn concentrations, although some variations have been noted. Skibniewski et al. (2010) found no statistically significant sex-based differences in Mn concentrations in European bison from the Bialowieza Primeval Forest across various tissues, including the liver (10.2 mg/kg), kidney (4.6 mg/kg), and hair (15.2 mg/kg). However, female European bison had slightly higher Mn levels in hair (16.0 mg/kg) compared to males (14.0 mg/kg), while males showed higher Mn levels in the hoof (4.1 mg/kg) than females (2.3 mg/kg). In contrast, Klich et al. (2023) reported statistically significant differences in liver Mn concentrations between sexes in European bison from Poland, while an earlier study by the same author (Klich et al., 2021) found no relation between sex and Mn levels in the liver. Similarly, Durkalec et al. (2018) observed no significant differences in liver Mn concentrations between female (0.240-4.190 mg/kg) and male (0.480-4.350 mg/kg) European bison in Poland. These findings suggest that while some minor variations in Mn concentrations may occur between sexes, they are generally not statistically significant, with Mn levels more influenced by environmental factors than by sex.

4.2.7.2. Age

No reported articles in this review that covered the effect of age on the concentrations of Mn.

4.2.7.3. Nutrition

The effects of nutrition on Mn statuses in bison highlight minimal differences between grass- and grain-finished diets, but significant variations between different cuts of meat and comparisons with beef. Marchello and Driskell (2001) found no significant difference in Mn concentrations between grass-finished and grain-finished American bison, with grass-finished meat showing Mn levels of 11.5 µg/100g and grain-finished meat at 13.4 µg/100g. However, among grass-finished bison cuts, Mn concentrations varied slightly, with clod containing the highest Mn levels (13.5 µg/100g) and top round the lowest (9.91 µg/100g). Marchello et al. (1998) also observed that different bison muscle cuts had varying Mn levels, with sirloin (14.6 µg/100g) significantly higher than ribeye (12.5 µg/100g) and top round (13.1 µg/100g). Comparatively, bison meat contains lower Mn than beef, with Marchello et al. (1989) reporting Mn concentrations of 0.007 mg/100g in bison and 0.013 mg/100g in beef, a significant difference. Additionally, Klich et al. (2021) found no correlation between age and Mn concentrations in the liver of European bison from Poland, suggesting that Mn levels in bison are influenced more by diet and meat cut rather than age. Overall, while diet does not significantly alter Mn levels in bison meat, differences between cuts and species highlight the nutritional distinctions in Mn content.

4.2.7.4. Health/Disease

The scoping review identified only one study investigating the relationship between health conditions and Mn statuses in bison, specifically focusing on European bison with balanoposthitis. In this study, Dębska et al. (2005) measured serum Mn concentrations in both healthy and balanoposthitis-diagnosed European bison, finding no significant difference between the two groups, with both having Mn levels of 0.12 $\mu\text{mol/l}$. This lack of difference has the authors suggest that Mn concentrations in serum do not appear to be influenced by the presence of balanoposthitis or the overall health status of the bison.

4.2.7.5. External Environment

Studies investigating Mn statuses in bison across different management environments and locations reveal notable variations depending on habitat and management conditions. MacNeil et al. (1990) compared Mn concentrations in liver and kidney tissues of American bison from Wood Buffalo National Park and a game ranch, finding that the game ranch bison had higher Mn levels in both the liver (3.19 ppm) and kidney (1.44 ppm) compared to bison from Wood Buffalo National Park (liver: 2.31 ppm, kidney: 0.92 ppm). Based on cattle nutritional standards, the game ranch bison were classified as having adequate Mn levels, while those from Wood Buffalo were marginal. In Poland, however, Mn concentrations showed no significant relation to site location. Klich et al. (2021) found no significant differences in Mn levels across various locations, while Durkalec et al. (2018) observed no significant difference between European bison from Bialowieza and Smardzewice (Mn liver concentrations: 0.240-4.350 mg/kg wet weight in Bialowieza versus 2.4-3.340 mg/kg in Smardzewice). In terms of management conditions, Durkalec et al. (2018) found significantly different Mn levels between free-range and captive European bison, with Mn deficiencies more prevalent in free-range animals (37%)

compared to captive ones (20%). The study further suggested that liver tissue may not be a reliable indicator of Mn deficiency and recommended measuring Mn levels in heart muscle or plasma for a more accurate assessment of Mn status in bison. These findings emphasize the influence of environmental and management factors on Mn levels, particularly with more deficiencies observed in free-range populations.

4.2.8. Iron (Fe)

4.2.8.1. Sex

Research in Fe statuses in bison across different sexes show minimal significant differences between males and females. In Yellowstone, Zaugg et al. (1993) reported that serum Fe concentrations in American bison ranged from 41-170 µg/dl in bulls and 52-186 µg/dl in cows, with no significant sex-based trends. Similarly, research by Kosla et al. (2013) on European bison found no significant differences in Fe content across various tissues, including the liver, kidney, muscle, rib, and hoof, despite slightly higher Fe concentrations in females across most tissues, such as the liver (270.75 mg/kg fresh tissue in females versus 246.88 mg/kg in males) and kidney (161.29 mg/kg in females versus 146.00 mg/kg in males). In contrast, male European bison had higher Fe levels in the hoof (70.33 mg/kg dry matter) compared to females (32.89 mg/kg). Hair Fe concentrations also showed no significant difference between sexes, with males averaging 133.62 mg/kg and females 110.77 mg/kg (Kosla et al., 2011). Klich et al. (2021) also found no sex-based relationship in hepatic Fe concentrations across different European bison sites in Poland. In terms of meat cuts, Galbraith et al. (2006) observed that sirloin had the highest Fe concentration in bulls (3.15 mg/100g), with significant differences between specific cuts, such as bottom roll (2.61 mg/100g) and clod (3.08 mg/100g). In heifers, the clod (3.10 mg/100g) and sirloin (2.56 mg/100g) were also significantly different. Overall, while some

tissue-specific variations exist, sex does not appear to significantly influence Fe status in bison within the articles reviewed.

4.2.8.2. Age

Iron statuses in bison across different age groups show distinct differences in Fe concentrations between calves and adults, particularly in certain tissues. In American bison from Yellowstone, Zaugg et al. (1993) reported that serum Fe concentrations were generally higher in calves (88-211 µg/dl) compared to adults (41-186 µg/dl), suggesting that younger bison may have higher circulating Fe levels. Similarly, Kosla et al. (2013) found significant age-related differences in Fe content in various tissues of European bison. Adult bison had notably higher Fe concentrations in the liver (342.45 mg/kg fresh tissue) and muscle (111.15 mg/kg) compared to calves (liver: 237.30 mg/kg; muscle: 69.55 mg/kg), indicating that Fe accumulates more in these tissues as bison age. However, in other tissues, such as the rib and hoof, the pattern was reversed, with calves having higher Fe concentrations in the rib (41.53 mg/kg in calves versus 31.00 mg/kg in adults) and hoof (54.90 mg/kg in calves versus 13.65 mg/kg in adults). Kosla et al. (2011) also examined Fe concentrations in hair across age groups and found no significant difference between calves (127.00 mg/kg) and adults (100.67 mg/kg), suggesting that hair may not reflect the age-related changes in Fe seen in other tissues. Overall, these studies indicate that Fe concentrations in bison vary significantly with age, particularly in the liver and muscle, where adults tend to accumulate more Fe over time.

4.2.8.3. Nutrition

The impact of nutrition on Fe statuses in bison reveals minor differences based on diet type. Marchello and Driskell (2001) found no significant difference in Fe concentrations between

grass-finished and grain-finished American bison. Across different cuts of grass-finished bison, the Fe content was consistent, with ribeye, top sirloin, and clod all approximately around 3.0 mg/100g, except for ribeye and top round at 2.7 mg/100g. However, differences between cuts were more pronounced in grain-finished bison. Marchello et al. (1998) reported that ribeye (2.8 mg/100g) had significantly lower Fe levels than sirloin (3.0 mg/100g), top round (2.9 mg/100g), and clod (3.0 mg/100g), indicating variation in Fe distribution across muscle types. Additionally, in a comparison of bison and beef, Marchello et al. (1989) found that bison had significantly higher Fe content in the longissimus muscle (2.6 mg/100g) compared to beef (1.8 mg/100g), highlighting bison meat as a richer source of Fe. These findings suggest that while diet does not drastically affect Fe content in bison meat, there are notable differences between specific cuts and between bison and other meat sources like beef.

4.2.8.4. Health/Disease

Studies exploring the relationship between health conditions and Fe statuses in bison suggest that Fe concentrations are generally stable across various disease states, with a few exceptions. Marczuk et al. (2015) found that European bison diagnosed with chronic liver flukes showed no evidence of changes in liver Fe concentrations, while domestic ruminants in the same study displayed slight changes in Fe levels depending on the presence of liver flukes. Similarly, Klich et al. (2023) investigated comorbidities in European bison and found that Fe concentrations in the liver did not correlate with any other elements or comorbid conditions, leading the researchers to exclude Fe from further analysis regarding disease relationships. In contrast, Dębska et al. (2005) found a significant difference in serum Fe concentrations between European bison diagnosed with balanoposthitis (35.89 $\mu\text{mol/l}$) and healthy individuals (56.37 $\mu\text{mol/l}$), with the diagnosed animals showing higher Fe levels compared to cattle reference data.

Although Fe levels remained stable in most cases, other trace elements like Cu and Se showed notable changes in relation to health conditions. Klich et al. (2023) observed that as the number of comorbidities increased, Cu concentrations decreased, contributing to a weakened state in the bison. They hypothesized that this imbalance in trace elements, combined with parasitic infestations, likely contributed to reduced weight and birth rates in the affected populations.

4.2.8.5. External Environment

Findings for Fe statuses in bison across different management practices, environments, and locations reveal notable variations influenced by habitat conditions. MacNeil et al. (1990) compared American bison from Wood Buffalo National Park and a game ranch, finding that Fe concentrations in the liver and kidney were higher in the game ranch bison (liver: 3.19 ppm, kidney: 1.44 ppm) compared to those from Wood Buffalo National Park (liver: 2.31 ppm, kidney: 0.92 ppm). In comparison to cattle data, the nutritional status for Fe in bison was determined: from Wood Buffalo National Park, Fe concentrations were considered marginal, while the game ranch bison had adequate Fe concentrations in both liver and kidney. This suggests that management conditions, such as controlled feeding and habitat quality, may influence Fe levels in bison. In a separate study, Klich et al. (2021) analyzed liver Fe concentrations in European bison from four different sites in Poland, finding that only two of the sites showed significant differences in Fe levels, while the others did not. These findings highlight the role that geographic location and environmental conditions play in determining Fe status, though the specific factors contributing to differences in Fe concentrations remain unclear. Overall, these studies emphasize that both natural environments and management practices, such as those seen in game ranches, can affect the Fe nutritional status of bison, with

bison in managed environments typically exhibiting more adequate Fe levels than those in less controlled habitats.

4.2.9. Copper (Cu)

4.2.9.1. Sex

The scoping review identified only one study investigating Cu statuses in bison based on sex. Durkalec et al. (2018) examined Cu concentrations in the liver of European bison from Poland and found no significant differences between males and females. The study reported a Cu range of 0.870-29.22 mg/kg wet weight for females and 2.03-49.170 mg/kg for males, with both sexes exhibiting broad variation in Cu levels.

4.2.9.2. Age

No reported articles in this review that covered the effect age on the concentrations of Cu.

4.2.9.3. Nutrition

Studies investigating the influence of nutrition on Cu statuses in bison highlight slight differences based on diet type and variations across different meat cuts. Marchello and Driskell (2001) found that grass-finished American bison had slightly higher Cu concentrations in raw separable lean meat (160.0 µg/100g) compared to grain-finished bison (142.0 µg/100g), though the difference was not significant. The Cu content was also assessed across various cuts, including ribeye (140 µg/100g), top sirloin (183 µg/100g), top round (145 µg/100g), and clod (172 µg/100g), with no significant differences between cuts. In a separate study, Marchello et al. (1998) reported that for bison fed concentrate diets, the sirloin cut had significantly higher Cu levels (155 µg/100g) compared to other cuts such as ribeye (130 µg/100g) and top round (135 µg/100g). Additionally, Marchello et al. (1989) compared Cu concentrations between bison and

beef, finding that bison had significantly lower Cu levels in the longissimus muscle (0.09 mg/100g) compared to beef (0.13 mg/100g). These findings suggest that while diet (grass vs. grain) may not significantly impact Cu levels in bison meat, there are notable differences between specific cuts and in comparison, to other meats like beef, with bison generally having lower Cu concentrations.

4.2.9.4. Health/Disease

Papers examining the relationship between health conditions and Cu statuses in bison suggest that Cu deficiencies may be linked to various disease states, but the overall impact varies across different conditions. Schillhorn van Veen et al. (1991) found that American bison necropsied after death had low liver Cu levels (8.1-8.4 ppm wet weight), which were comparable to low Cu levels observed in cattle. These deficiencies were also accompanied by low Se levels. Similarly, Rhodes et al. (2018) reported low liver Cu concentrations (10 ppm) in euthanized American bison, speculating that parasitic infestations, like coccidia, could interfere with Cu absorption, as well as other nutrients. The authors stipulated that this malabsorption could be further exacerbated by increased absorption of competing minerals such as Se, Mo, or Zn. In European bison, Dębska et al. (2005) found no significant difference in serum Cu levels between individuals with balanoposthitis (11.59 $\mu\text{mol/l}$) and healthy bison (10.52 $\mu\text{mol/l}$), with both groups falling within cattle reference ranges. However, Klich et al. (2023) observed that European bison with fewer lesions had higher hepatic Cu concentrations, suggesting that Cu deficiencies may be associated with greater susceptibility to comorbidities. These findings indicate that while Cu deficiency does not always correlate with specific diseases like balanoposthitis, it may play a role in the overall health and resilience of the animal.

4.2.9.5. External Environment

Cu statuses in bison across different environments and management conditions highlight the influence of location, habitat, and human activities on Cu concentrations. Skibniewska et al. (2006) reported that European bison from Białowieża Forest had Cu concentrations below standard values in various tissues, with levels of 26.10 mg/kg in the liver, 21.33 mg/kg in the kidney, and 16.48 mg/kg in the hair. These deficiencies suggest environmental factors in Białowieża lands may impact Cu absorption. Similarly, MacNeil et al. (1990) found that American bison from Wood Buffalo National Park had lower liver Cu concentrations (15.3 ppm) compared to those from a game ranch (32.4 ppm), though kidney Cu levels were adequate in both populations. This discrepancy may reflect differences in diet and habitat management, as the game ranch provided a more controlled environment. Klich et al. (2021) further demonstrated how local agricultural practices affect Cu levels, finding that bison from the Knyszyńska region had significantly lower hepatic Cu concentrations due to intensive farming, where treatments of nitrogen and P may dilute Cu content in crops. Meanwhile, Durkalec et al. (2018) found no significant difference in Cu levels between bison from Białowieża and Smardzewice, nor between free-range and captive bison, though Cu deficiencies were widespread, affecting 85% of captive and 88% of free-range bison. These findings indicate that both natural and managed environments can have deficiencies due to environmental conditions and agricultural impacts.

4.2.10. Zinc (Zn)

4.2.10.1. Sex

Studies studying Zn statuses in bison across different sexes generally do not report significant differences between males and females. Kosla et al. (2004) reported a tendency for European bison males to have higher Zn levels in various tissues, with liver Zn concentrations

averaging 172.7 mg/kg in males compared to 134.6 mg/kg in females. Despite this trend, no statistically significant sex-based differences were observed across tissues. Similarly, Durkalec et al. (2018) found wide variations in liver Zn concentrations in European bison from Poland, ranging from 30.69 to 430.12 mg/kg in males and 33.68 to 99.57 mg/kg in females, but again, there were no significant differences between sexes.

4.2.10.2. Age

The scoping review revealed only one study investigating Zn statuses in bison across different age groups. Kosla et al. (2004) found that Zn concentrations in the kidneys and liver tended to increase with age. In their study, older European bison (over two years) had higher Zn levels in the kidneys (98.4 mg/kg) compared to younger bison (80.2 mg/kg), a difference that was statistically significant. Similar trends were observed in the liver, where older bison had Zn concentrations of 181.6 mg/kg, compared to 134.1 mg/kg in younger individuals, though this difference was not statistically significant. In contrast, Zn concentrations in ribs and hair showed no significant differences between younger and older bison, indicating that age primarily affects Zn accumulation in certain internal organs like the kidney and liver.

4.2.10.3. Nutrition

Research investigating the effects of nutrition on Zn statuses in bison reveal variations in Zn concentrations based on diet type and meat cuts. Marchello and Driskell (2001) found no significant difference in Zn levels between grass-finished (3.3 mg/100g) and grain-finished (3.8 mg/100g) American bison, suggesting that diet type has minimal impact on Zn content in bison meat. However, Zn concentrations varied significantly between different cuts of grass-finished bison, with the clod (4.3 mg/100g) having the highest Zn content, significantly different from the

top sirloin (3.3 mg/100g) and ribeye (3.0 mg/100g), while the top round (2.8 mg/100g) had the lowest levels. Similarly, Marchello et al. (1998) observed significant differences in Zn concentrations across cuts of bison fed concentrate diets, with clod (5.0 mg/100g) and ribeye (3.2 mg/100g) differing from other cuts like top round (3.5 mg/100g). When comparing bison and beef, Marchello et al. (1989) found that beef had significantly higher Zn levels (3.4 mg/100g) than bison (2.8 mg/100g), highlighting bison as a leaner meat with slightly lower Zn content.

4.2.10.4. Health/Disease

Research examining Zn statuses in bison in relation to health and disease conditions reveals that Zn levels can fluctuate based on specific illnesses, though clear patterns are not always consistent across different conditions. In American bison, Rhodes et al. (2018) found elevated hepatic Zn levels (125 ppm) in animals euthanized due to poor body condition, alongside a high presence of intestinal parasites. The authors concluded that this increase in Zn likely contributed to the observed Cu deficiency, as Zn can interfere with Cu absorption, compounding the animals' health problems. Similarly, Klich et al. (2023) found that European bison in Poland, euthanized for various clinical illnesses, showed significantly higher Zn concentrations in the liver as the number of lesions increased, particularly in animals classified in the more severe lesion groups. The number of multiple types of lesions was strongly associated with higher Zn levels in hepatic tissue, suggesting a possible connection between disease severity and Zn metabolism. In contrast, Dębska et al. (2005) found no significant difference in serum Zn levels between European bison with balanoposthitis (10.54 $\mu\text{mol/l}$) and healthy bison (13.18 $\mu\text{mol/l}$), with both groups falling within cattle reference ranges. These findings indicate that while Zn levels may fluctuate in response to specific diseases or parasitic infections, the

relationship between Zn and overall health in bison remains complex and may be influenced by interactions with other trace minerals, such as Cu.

4.2.10.5. External Environment

The influence of external environment, management, and location on Zn statuses in bison highlights significant variations in Zn concentrations based on habitat and management conditions. MacNeil et al. (1990) compared American bison from Wood Buffalo National Park and a game ranch, finding that liver Zn concentrations were higher in bison from Wood Buffalo (52.8 ppm) than those from the game ranch (34.3 ppm), while kidney Zn levels were similar between both sites (22.4 ppm for Wood Buffalo and 21.4 ppm for the game ranch). Both locations had adequate Zn levels compared to cattle reference data. In Poland, Klich et al. (2021) analyzed Zn concentrations in bison liver across multiple sites and found significant differences, with the highest levels in the Bieszczady Mountains and the lowest in the Knyszyńska Forest. The authors suggested that higher Zn concentrations in Bieszczady soils contributed to the difference, while in Knyszyńska, the lower Zn intake was linked to feeding on Zn-deficient crops, exacerbated by soil pH. Durkalec et al. (2018) found no significant difference in liver Zn concentrations between Bialowieza and Smardzewice, but they did report a significant difference between free-range and captive bison, with free-range animals showing higher Zn levels (38.14-430.12 mg/kg wet weight) compared to captive ones (30.96-91.06 mg/kg). The authors hypothesize that Zn deficiencies were more prevalent in captive bison (37%) compared to free-range bison (3%) and suggest that natural foraging may better to support adequate Zn intake.

4.2.11. Other Minerals

4.2.11.1. Sex

Articles analyzing the mineral statuses of bison across different sexes reveal minimal significant differences, though some trends emerge in specific elements. Durkalec et al. (2018) analyzed liver concentrations of various minerals in European bison and found that most minerals, including Al, Cd, Hg, and Pb, did not show significant differences between sexes. However, Ag concentrations were significantly higher in males (0.0015-0.0640 mg/kg wet weight) than females (0.0011-0.0463 mg/kg). Klich et al. (2023) also found that males had higher hepatic concentrations of Mo and Ni, with six elements, including these two, consistently lower in females. This trend of males having higher mineral concentrations was echoed in Kosla et al. (2016), who observed that Sr and Cs levels were higher in the hooves of males (0.917 mg/kg for Sr and 0.017 mg/kg for Cs) compared to females (0.755 mg/kg for Sr and 0.010 mg/kg for Cs), with Cs being significantly different. In contrast, other studies found no significant sex-based differences for minerals like P, titanium, vanadium, Sr, and barium in hair (Kosla et al., 2010; Kosla et al., 2011). Zaugg et al. (1993) also noted no significant differences in blood serum Cl levels between American bison bulls (102.11 mEq/L) and cows (104.46 mEq/L). Overall, while some elements, like Ag, Mo, and Cs, show sex-based differences, the majority of minerals do not vary significantly between male and female bison within the articles of this review.

4.2.11.2. Age

The influence of age on mineral statuses in Bison reveal varied patterns, with some minerals showing significant differences between calves and adults, while others remain relatively stable across age groups. For Cl concentrations in serum, Brzuski et al. (2010) found that adult American bison had higher Cl levels (94.9 mmol/L) than calves (90.75 mmol/L), a trend also observed by Vestweber et al. (1991), who reported significantly higher Cl levels in

bison older than 24 months (104.50 mmol/L) compared to those aged 7-23 months (102.81 mmol/L). In contrast, Zaugg et al. (1993) found overlapping Cl ranges for adults (88-110 mEq/L) and calves (98-107 mEq/L) in Yellowstone bison. Klich et al. (2023) noted that only Cd and Ni concentrations in the liver showed significant correlations with age, while Kosla et al. (2010) found significantly higher vanadium levels in the hair of older European bison (0.686 mg/kg) compared to calves (0.260 mg/kg). Sr and Cs levels showed mixed results: in muscle tissue, Sr was significantly higher in adults (2.133 mg/kg) than in calves (0.720 mg/kg), while Cs was higher in calves (0.126 mg/kg) than in adults (0.070 mg/kg) (Kosla et al., 2016). However, Sr concentrations in hooves were significantly lower in adults compared to calves. Additionally, Shupe et al. (1987) linked the severity of dental fluorosis and wear in American Bison to both age and fluoride exposure. Overall, these findings suggest that age plays a variable role in mineral statuses, with some elements like Cd, Ni, V, and Sr showing significant age-related differences, while others like Cl display more subtle variations depending on the study.

4.2.11.3. Nutrition

Bison nutrition and mineral statuses only exhibited one study specifically investigated the impact of other trace elements in relation to diet. Wlostowski et al. (2006) examined the accumulation of Cd in the liver and kidneys of European bison and Polish cattle, finding significantly higher Cd concentrations in bison tissues. The liver Cd concentration in European bison was 0.45 mg/kg, compared to just 0.02 mg/kg in cattle, while Cd levels in the kidneys were also markedly higher in bison (2.79 mg/kg) versus cattle (1.30 mg/kg). The authors concluded that these differences were directly related to the higher levels of Cd found in the grasses consumed by bison, which were twice as high as those grazed by cattle. This study highlights the

strong correlation between dietary intake and trace element accumulation in tissues, emphasizing the need for further research into how different diets affect trace mineral accumulation in bison.

4.2.11.4. Health/Disease

In this scoping review, one study specifically investigated the relationship between other trace elements, health problems, and mineral absorption. Rhodes et al. (2018) analyzed liver and fecal samples from American bison and found toxic levels of Se and Mo at 4.2 ppm, which were linked to deteriorating health conditions. The study suggested that the elevated levels of Mo, along with other trace elements, likely contributed to malabsorption issues, particularly for Cu, which is critical for various physiological processes. Additionally, the presence of parasites in the digestive systems of these animals further compounded the health problems by interfering with nutrient absorption. This research highlights the complex interplay between trace elements and overall health, indicating that imbalances in elements like Mo, combined with parasitic infections, can significantly affect mineral absorption and lead to worsening health outcomes in bison.

4.2.11.5. External Environment

Findings for the influence of external environments, management styles, and geographic locations on the mineral statuses of bison reveal significant deviations in trace element concentrations across different habitats and management conditions. Durkalec et al. (2018) found no significant differences in mineral concentrations—including Ag, Al, Cd, and Hg—between captive and free-ranging European bison, suggesting that management style (captive vs. free-ranging) does not significantly impact the accumulation of these trace elements. However, when comparing liver mineral concentrations by geographic location, significant differences were

found for arsenic, Cr, Ni, and Pb. For instance, arsenic levels in the liver were higher in bison from Smardewice (0.0063-0.0163 mg/kg) compared to those from Bialowieza (0.0009-0.0122 mg/kg), and similar trends were observed for Cr, Ni, and Pb, with Smardewice bison generally exhibiting higher concentrations. Klich et al. (2021) also found that Mo concentrations were lower in bison from the Bieszczady Mountains compared to other regions, likely due to the acidic soil in the region, which limits Mo uptake by plants. Other elements such as beryllium, Co, lithium, silicon, titanium, and Cd showed site-specific correlations, reflecting the strong influence of local environmental factors on mineral accumulation. Similarly, Kośła et al. (2006) found higher Al concentrations in the hair (59.6 mg/kg) and hoof (36.5 mg/kg) compared to the rib (17.9 mg/kg), indicating tissue-specific accumulation patterns in free-ranging bison in Poland. In North American bison, MacNeil et al. (1990) compared trace element concentrations in bison from Wood Buffalo National Park and a game ranch, finding that while all mineral levels were adequate, bison from Wood Buffalo had higher Cd levels in the liver (0.37 mg/kg) and kidney (2.75 mg/kg) compared to ranch bison. The geographic and environmental factors influencing these mineral concentrations demonstrate how habitat, soil composition, and local forage can significantly affect trace element statuses in bison across different locations.

4.3. Vitamins

4.3.1. Vitamin A

4.3.1.1. Sex

A single study investigated the relationship between sex and vitamin A (retinol) concentrations in American bison within this review, comparing heifers and bulls across different cuts of meat. Galbraith et al. (2006) found that vitamin A levels varied among cuts but showed no significant differences within sex classes. For bulls, retinol concentrations ranged

from 1.74 $\mu\text{g}/100\text{g}$ in the eye round to 2.39 $\mu\text{g}/100\text{g}$ in the blade, while in heifers, the clod and sirloin cuts contained 1.95 $\mu\text{g}/100\text{g}$ and 2.18 $\mu\text{g}/100\text{g}$, respectively. While the study found that vitamin A concentrations were higher than those reported in earlier research by Marchello (1998), no significant differences in vitamin A levels were observed between the sexes. The study also noted a positive correlation between vitamin A and trans-fat content in bison meat, suggesting a potential link between dietary fat profiles and retinol levels. This research underscores that while vitamin A concentrations may vary across different cuts and exceed previously recorded levels, sex does not appear to significantly impact vitamin A status in bison meat.

4.3.1.2. Age

No reported articles in this review covered the effect of age on vitamin A concentrations in bison.

4.3.1.3. Nutrition

The effects of diet on vitamin A (retinol) and related metabolites in bison reveal notable differences based on nutrition type, particularly between grass- and grain-finished diets. Driskell et al. (2004) compared ribeye cuts from grass- and grain-finished American bison and found that while retinol concentrations were slightly higher in grass-finished bison (1.420 $\mu\text{g}/100\text{g}$) than grain-finished bison (1.250 $\mu\text{g}/100\text{g}$), this difference was not significant. However, beta-carotene levels were significantly higher in grass-finished bison (14.930 $\mu\text{g}/100\text{g}$) compared to grain-finished bison (0.063 $\mu\text{g}/100\text{g}$), likely due to the natural seasonality and beta-carotene content of grasses. Another study by Driskell et al. (1997) showed that vitamin A concentrations in American bison bulls ranged from 0.7-1.075 $\mu\text{g}/100\text{g}$ across diets, with the highest levels found

in bulls fed a diet rich in wheat, oats, and corn, whereas lower levels were found in bison on wheat by-products. When comparing bison meat to other retail meats, bison exceeded beef and turkey in vitamin A but not pork or chicken. Marchello et al. (1998) also found differences in vitamin A among bison meat cuts, reporting higher retinol in the sirloin (0.91 µg/100g) compared to clod (0.68 µg/100g). Additionally, van Vliet et al. (2023) noted that pasture-raised American bison had significantly higher levels of carotene diol, a metabolite with antioxidant properties, compared to grain-finished bison.

4.3.1.4. Health/Disease

No reported articles in this review that covered the effect of health/disease on vitamin A concentrations in bison.

4.3.1.5. External Environment

No reported articles in this review that covered the effect of external environment on vitamin A concentrations in bison.

4.3.2. Vitamin B

4.3.2.1. Sex

No reported articles in this review that covered the effect of sex on vitamin B concentrations in bison.

4.3.2.2. Age

No reported articles in this review that covered the effect of age on vitamin B concentrations in bison.

4.3.2.3. *Nutrition*

Studies investigating the impact of diet on vitamin B concentrations in bison reveal key differences between grass- and grain-finished diets as well as variability among meat cuts. Driskell et al. (2004) compared grass- and grain-finished American bison ribeye, finding that riboflavin and niacin levels differed significantly between diets. Grass-finished bison had lower riboflavin (0.073 mg), but higher niacin (3.040 mg) compared to grain-finished bison, likely due to protein differences in feed and niacin's reduced bioavailability in grains. In comparison to other meats, bison showed higher thiamin (0.045 mg/100g), B6 (0.253 mg/100g), and B12 (2.131 µg/100g) than pork, chicken, and turkey (Driskell et al., 1997). Marchello et al. (1998) further examined different American bison cuts, finding significant variations in B6 and thiamin across cuts, with the top round having higher B6 (281 µg/100g) and ribeye exhibiting lower thiamin levels (46.0 µg/100g). The influence of diet on vitamin B metabolism was also explored by van Vliet et al. (2023), who noted higher levels of pyridoxine, a B6 metabolite, in grain-finished American bison, possibly due to corn-based feed. Additionally, Driskell et al. (2000) observed wide variation in riboflavin and niacin across cuts, attributed to factors like age, diet, and seasonal changes, aiming to reflect average nutrient values in bison for consumers. Lakritz et al. (1998) tested for vitamin B loss in bison under gamma radiation for meat sterilization, finding no significant change in riboflavin or thiamin, thus supporting the nutritional stability of bison meat. These studies underscore how diet, cut, and processing conditions affect the vitamin B profile in bison, with grass-finished meat offering higher niacin and lower riboflavin, and certain cuts providing distinct nutrient concentrations.

4.3.2.4. *Health/Disease*

No reported articles in this review that covered the effect of health/disease on vitamin B concentrations in bison.

4.3.2.5. *External Environment*

No reported articles in this review that covered the effect of external environment on vitamin B concentrations in bison.

4.3.3. *Vitamin C*

4.3.3.1. *Sex*

No reported articles in this review that covered the effect of sex on vitamin C concentrations in bison.

4.3.3.2. *Age*

No reported articles in this review that covered the effect of age on vitamin C concentrations in bison.

4.3.3.3. *Nutrition*

Analyzing vitamin C concentrations in bison across different diets reveals that bison meat is generally a poor source of vitamin C, regardless of feeding regimen or meat cut. Driskell et al. (2004) found undetectable levels of vitamin C in both grass- and grain-finished American bison ribeye, suggesting that bison meat contributes minimally to dietary vitamin C. In comparison to other meats, Driskell et al. (1997) reported that vitamin C levels in American bison were similarly undetectable, whereas meats like chicken and pork contained detectable amounts, making bison a comparatively low source of vitamin C. Marchello et al. (1998) also noted

undetectable vitamin C concentrations across multiple American bison cuts from animals fed grain diets, reinforcing the minimal presence of this vitamin in bison meat products. However, van Vliet et al. (2023) observed that grain-finished American bison exhibited higher ascorbate, a vitamin C metabolite, than grass-finished animals. Although vitamin C is not essential for ruminants, higher ascorbate levels could enhance meat shelf stability and quality. Collectively, these studies highlight that while bison meat lacks significant vitamin C, certain feeding practices may slightly improve meat preservation, even if the nutritional impact remains negligible.

4.3.3.4. Health/Disease

No reported articles in this review that covered the effect of health/disease on vitamin C concentrations in bison.

4.3.3.5. External Environment

No reported articles in this review covered the effect of external environment on vitamin C concentrations in bison.

4.3.4. Vitamin E

4.3.4.1. Sex

No reported articles in this review that covered the effect of sex on vitamin E concentrations in bison.

4.3.4.2. Age

No reported articles in this review that covered the effect of age on vitamin E concentrations in bison.

4.3.4.3. *Nutrition*

Studies examining the effects of diet on vitamin E (tocopherol) levels in bison suggest that diet type and meat cut slightly influence tocopherol concentrations, although overall vitamin E levels remain low in bison meat compared to other meats. Driskell et al. (2004) reported no significant difference in alpha-tocopherol (vitamin E) between grass-finished (0.137 mg) and grain-finished (0.161 mg) American bison ribeye, suggesting that finishing diet minimally impacts vitamin E levels. However, van Vliet et al. (2023) found that pasture-finished American bison had statistically higher alpha-tocopherol levels, while beta- and gamma-tocopherols were nearly six times higher in grain-finished bison, likely due to corn and alfalfa in grain diets, which are rich in these nutrients. Comparing different meat cuts, Marchello et al. (1998) found no significant difference in alpha-tocopherol levels across cuts such as ribeye (38.7 µg/100g) and top round (51.9 µg/100g). Comparisons with other meats reveal American bison's relatively low tocopherol content; Driskell et al. (1997) found that combined alpha- and gamma-tocopherols were lower in bison than in beef, pork, chicken, and turkey. In a direct comparison, Galbraith et al. (2016) reported that bison had higher alpha-tocopherol and total vitamin E concentrations than beef but lower alpha-tocotrienol levels. Additionally, Lozicki et al. (2017) observed that European bison had higher alpha-tocopherol levels than beef, but not compared to their hybrid crosses, Zubrons. Authors attributed the difference of vitamin E between European bison and beef to greater intake of green forage from the bison. For preservation, Lakritz et al. (1998) found that gamma radiation sterilization did not affect vitamin E levels in American bison or other exotic meats, suggesting stable tocopherol content post-processing. These findings emphasize that while diet may enhance certain tocopherol isomers, bison generally has low vitamin E concentrations, with slight differences by cut and finishing method.

4.3.4.4. *Health/Disease*

No reported articles in this review that covered the effect of health/disease on vitamin E concentrations in bison.

4.3.4.5. *External Environment*

No reported articles in this review that covered the effect of external environment on vitamin E concentrations in bison.

4.4. *Limitations*

To the author's knowledge, this is the first scoping review on vitamin and mineral concentrations within tissues of bison; however, this scoping review is subject to several important limitations. This review does not focus exclusively on a single bison species, encompassing both American and European bison. This introduces variability, as these species may have different ecological, physiological, and nutritional profiles. Terminological inconsistencies in the literature also pose a challenge; the terms "bison" and "buffalo" are sometimes used interchangeably, leading to potential ambiguity about which species is being referenced in certain studies. Articles with unclear species designation were excluded from this review; however, this approach may have led to the omission of studies relevant to the population of interest, potentially limiting the breadth of data available for analysis.

Additionally, although this was not specifically assessed, there was considerable methodological inconsistency across studies. Differences in sampling procedures, analytical methods, and reporting standards were not accounted for, which could affect the comparability of findings.

Additionally, the choice of tissues analyzed in many studies may not fully represent the overall mineral or vitamin status of the animals, as these concentrations are influenced by complex

physiological interactions involving multiple tissues. Sampling bias is also a concern, particularly for European bison, as samples are often collected opportunistically due to the species' protected status. These samples frequently come from animals culled due to illness, injury, or advanced age, which may not reflect the nutrient status of the broader population. Finally, variability in the terminology used to describe management practices adds complexity to the interpretation of results. Terms like "free-range," "enclosed," "captive," and "ranching" were often used inconsistently or interchangeably across studies, complicating efforts to make meaningful comparisons of mineral and vitamin concentrations across different management contexts.

4.5. Conclusions

This scoping review highlights significant gaps in our understanding of mineral and vitamin concentrations within bison. Research on vitamins is minimal and has primarily focused on nutrient content of consumable products rather than examining vitamin levels across different tissues with interest in the status of the animal. There are notable gaps in research on trace elements as well; while studies have explored mineral concentrations in the context of grass-fed versus grain-fed diets, there is limited investigation into how these concentrations vary by health status, sex, or age. Moreover, few studies have examined blood serum mineral levels over time or across seasons, even though many bison reside and are raised in range environments where nutrient availability likely fluctuates. Seasonal and longitudinal studies could offer valuable insights into how mineral levels in bison shift in response to environmental changes. There is also an imbalance in research focus between American bison and European bison. While American bison studies emphasize the nutrient profile of meat, there is relatively less research attention on the assessment of overall mineral status of these animals. In contrast, research on

European bison places a greater emphasis on mineral and vitamin status, likely due to the protected status of the species in Poland, where there is a strong focus on health monitoring.

Overall, the current literature on bison nutrition reveals a limited focus on vitamin concentrations in tissues other than meat, and a need for more comprehensive studies on mineral and vitamin status across different contexts and life stages of bison populations.

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CHAPTER 2 – CHARACTERIZING THE VITAMIN AND MINERAL STATUS OF FARMED AMERICAN BISON IN THE UNITED STATES²

1. Introduction

The American bison (*Bison bison*) is a historic animal of North American and has made an entrance into the animal agriculture industry within the last decade (Freese et al., 2007; USDA, 2022). The bison industry is growing in many areas: in population size within the United States and other countries such as Canada, in interest within the scientific community, as well as in social sectors like tribal communities. (Galbraith et al., 2014; National Bison Association, 2024; USDA, 2022; USDA, 2024). This increase of interest of bison in agriculture spans over many areas of production, but nutrition of bison in a confined or controlled environment is a large area for potential studies (Hawley et al., 1978; Marchello et al., 1998; Saskatchewan Agriculture & Food, 1999; Hecker et al., 2021). Largely, current interest in bison nutrition stems from feed utilization, gastro-intestinal health, and comparison of bison to beef on common diets and rations found in today's feedlots, as well on grass-fed operations (Driskell et al., 2004; Lulka, 2006; Bergmann, 2017; Janssen et al., 2021). However, there is a lack of information surrounding the mineral and vitamin requirements and status of bison, even though vitamins and minerals are known for all living species as being crucial components for biological functioning (Wagner et al., 2023, Puls, 1994, Spears, 2000).

Minerals are key parts of nutrition and help with many processes within the body such as muscle growth, reproduction, and many others by being activators of enzymes (Puls, 1994; McDowell, 2006; Becka and Hall, 2023; Wagner et al., 2023). Current studies that have investigated the status of minerals within bison have been few (cite), but predominantly focus on age and sex effects, as well as the impacts of different finishing diets (grass or grain-fed) on final

meat products. A study from Galbraith et al. (2006) investigated different retail cuts of bison and their mineral contents across different sexes. Results identified slight differences in iron, calcium, and sodium concentrations between certain meat cuts, and noted that iron levels in muscle were greater than compared to beef cattle of similar retail cuts (Galbraith et al., 2006). Another study by Marchello et al. (1989) examined meat products and the difference of beef cattle and bison on a concentrate diet. When investigating multiple macro- and micro-minerals of the longissimus muscle, they reported significant differences of all minerals, except for sodium concentrations between bison and beef (Marchello et al., 1989). Other studies have focused on the European bison (*Bison bonasus*) and possible health concerns correlated to mineral concentrations within tissues (Kośła et al., 2015; Marczuk et al., 2015; Klich et al., 2021; Klich et al., 2023). A study by Durkalec et al. (2018) examined various micro-mineral concentrations within the livers of free-ranging European bison. Many micro-minerals can be toxic to animals, even in small quantities, and accumulation of these can lead to several health problems (Durkalec et al., 2018; Buchweitz et al., 2023). European bison from this study were found to have higher concentration of cadmium and chromium with increase of age and an overwhelming majority of animals with low and deficient quantities of copper and selenium (Durkalec et al., 2018). Along with toxicities, mineral deficiencies can deafen the immune system and lead to greater disease susceptibility. Likewise, deficiencies have been shown to shunt growth and minimize metabolic pathway potentials in multiple different livestock species (Spears, 2000; Becka and Hall, 2023; Buchweitz et al., 2023; Wagner et al., 2023).

Vitamins act as coenzymes in metabolic reactions and closely tied to the function of the immune system (Smith, 2023; Wagner et al., 2023). They exhibits complex relationships with minerals, and can be fat or water soluble (Puls, 1994; NASEM, 2016; Wagner et al., 2023).

Studies in the beef industry are less common in vitamin concentrations than in mineral concentrations of tissues, but status in meat and milk are most common (O'Donovan, 1966; Hidioglou, 1989; McDowell, 2006). In bison, vitamins are even less studied, but research focused on vitamins exhibit similar areas of interest in meat concentrations. Studies have focused on concentrations of vitamin A and E and their effect on meat color stability, as well as relations of nutrient value relative to processing methods and in comparison to beef cattle (Lakritz et al., 1998; Driskell et al., 2004; Galbraith et al., 2006; Galbraith et al., 2016). Only a few studies have looked into potential health benefits for both animal and human with vitamin concentrations within muscle of bison (van Vliet et al., 2023), but vitamins still remain relatively unfamiliar and understudied within the field.

Although there is an increase in popularity of raising bison in a farmed/ranched setting, there is little knowledge about specific requirements of these critical vitamins and minerals within the diet of bison, as they have currently been based upon cattle requirements (Puls, 1994; NASEM, 2016). The Scientific Committee responsible for developing the Bison Code of Practice in Canada identified a gap in the bison research base regarding nutritional requirement information for bison, including vitamin and mineral requirements in their 2016 technical report (NFACC, 2017). This gap in knowledge is important to note because although bison are hardy and durable animals, they still need species-specific essential nutrients that maintains their health, animal welfare, and growth potentials in order to be raised successfully within a farmed setting (Vestweber et al., 1991a; NFACC, 2017; Rhodes et al., 2018; van Vliet et al., 2023). Therefore, the objectives of this study are to 1) obtain baseline mineral and vitamin status information via post-mortem sampling from bison slaughtered at commercial slaughter facilities and to 2) perform on-ranch baseline mineral and vitamin analysis of feed and water.

2. Materials and Methods

2.1. Sampling Plan

The population of interest was farmed American Bison (*Bison bison*) of varying ages, sexes, and ranch origins. From each bison, blood (plasma and serum), liver, kidney, and muscle were planned for sampling, as well as information about origin, age, sex, and predominant feed. Bison were chosen for sampling in order to meet an even distribution of different sexes, ages, and ranch locations. Due to the interest of seasonal differences, sampling was completed around the meteorological calendar and tried to evenly disperse collection from locations within each different season for both animal tissues, feed, and water samples. Tissue samples were either collected at a USDA-inspected commercial slaughter facility or a USDA-inspected mobile slaughter company, and all feed and water samples were collected at correlating ranches that animals for tissue sampling originated from. Communication was established with a predominate large ranching company to collaborate with scheduling of collection at slaughter facilities, and sampling decision of ranches was made upon the basis of frequency and number of animals sent during a year. Ranches where animals were collected from for sample analyzation were visited in each season (spring, summer, autumn, and winter) to obtain supplementary feed and water samples. The sampling time frame was from the winter of 2022 through spring of 2024.

2.2. Tissue Collection

Communication was first made with the USDA commercial slaughter facility or USDA-inspected mobile slaughter company to track which bison were being processed. Once a lot (group of same age and sex of fed animals) of bison was chosen for tissue sampling, sex, approximate age, and ranch origin were also recorded for data purposes. Tissue samples were collected post-mortem from animals processed at a commercial slaughter facility. The following

samples were collected from each bison: 2 blood samples collected after sticking of the carotid artery and approximately 50.0 grams of the liver (right lobe), kidney (caudal cross-section), and muscle (caudal cross-section of the diaphragmaticus pars costalis (hanging tender)). Fresh tissues were collected in pre-labeled Whirl-Pak® sample bags and blood samples were collected in pre-labeled Vacutainer® blood tubes (1 - k2/EDTA tube for plasma and 1 - clot activator tube for serum). Blood samples were temporarily stored on ice while tissue samples were either stored temporarily on dry ice. All samples were then taken back to the laboratory for further processing and tissues placed in long-term storage at -80°C.

2.2.1. Tissue Sample Processing

Blood tubes were centrifuged at 1,200 x g for 15 minutes within 24 hours of collection and supernatant was pulled off and transferred to pre-labeled 2 mL microcentrifuge tubes in duplicate for long-term storage at -80°C.

Liver, kidney, and muscle samples were removed from the -80°C freezer to thaw for at least three hours before further processing. After thawing, the samples were processed within 48 hours. Samples were cut into 2.5 cm cubes and placed into a bath of liquid nitrogen for approximately two minutes to freeze completely. Once frozen, a food-grade blender was used for the cut tissue to grind and homogenize the sample. A priming step was added before final grinding to prepare the cup for the sample by using a couple cubes of wanted sampled, ground, and then removed from the cup. Ground tissue samples were then stored back into a labeled Whirl-Pak® bag and placed in a -80°C freezer until further analysis. The blender and equipment were cleaned with DI water, soap, and 70% ethanol alcohol between each sample ground.

2.3. Feed and Water Collection

After initial tissue collection was completed, ranches where bison samples came from were visited seasonally for feed and water collection. Ranches were to be collected four times (once for each season) to gather a yearly snapshot of how the feed and water samples deviate throughout seasonal changes. Feed samples were taken from the ranch's feedyard and from composited forages from grazing lands throughout the ranch. Water consisted of a collection of well sources and natural sources that bison had access to. The ranch in South Dakota also had access to artisanal water sources that were also sampled for analysis. Feed samples were kept in labeled large Whirl-Pak® bags and water in 50.0 mL conical tubes. All samples were then brought back to the laboratory and stored at -50°C.

2.3.1. Feed Processing

After thawing to room temperature, all feed samples were weighed into a pre-weighed and labeled tin and recorded in grams. Feed samples were then dried in a 60°C oven for at least 24 hours, cooled to room temperature in a desiccator, and then recorded for dried weight to calculate for dry matter percentage. Once weighed, feed samples were ground in a Wiley mill (Thomas Scientific, Swedesboro, NJ) with a 2.0 mm particle screen. Ground feed samples were then stored back into a -50°C freezer until further analysis.

2.4. Mineral Analysis

2.4.1. Dry Matter and Ash Percentage

Like processed feed samples, liver, kidney, and muscle samples also were calculated for dry matter percentage. Acid-washed crucibles were weighed and recorded for weight in grams. Samples were weighed out for approximately 1 gram (± 0.5 grams) of sample and dried in a 60°C oven for at least 24 hours. Crucibles were then weighed back to determine

the dry matter percentage. Both feed samples and liver, kidney, and muscle samples were then heated at 600°C in a muffle furnace for at least 12 hours to obtain ash percentage.

2.4.2. *Wet Ash*

One of the duplicates of both plasma and serum samples was thawed and 0.1 mL of the sample was taken and pipetted into 5 mL tubes. 0.1 mL of 70% nitric acid was then added to each 5.0 mL tube and partially submerged in a 70°C water bath for 4 hours. After 4 hours, samples were taken off the water bath, cooled, and 0.1 mL of 30% hydrogen peroxide was added to each tube and placed back into the 70°C water bath for 2 hours. After finishing, tubes were pulled off the water bath, cooled, and then diluted with DI water to 1.0 mL of solution.

2.4.3. *Element Analysis*

All samples (liver, kidney, muscle, plasma, and serum) were sub-sampled and analyzed for Calcium (Ca), Cobalt (Co), Chromium (Cr), Copper (Cu), Iron (Fe), Potassium (K), Magnesium (Mg), Manganese (Mn), Molybdenum (Mo), Sodium (Na), Phosphorus (P), Sulfur (S), Selenium (S), and Zinc (Zn). A known mass or volume of each sample was initially wet-ashed in a microwave digester with HNO₃ (Titan MPSTM, PerkinElmer) at 200°C, 800 psi for 50 minutes. Elements were quantified via inductively coupled plasma-mass spectrometry (PerkinElmer; NexION 2000B).

2.5. *Vitamin Analysis*

All samples (tissues, plasma, and serum) were sub-sampled and sent for vitamin analysis of Vitamin A, Vitamin E (α -tocopherol and γ -tocopherol) and Vitamin K concentrations and extracted from tissues via saponification and analyzed using LC-MS/MS according to AOAC Official Methods (AOAC International. 2006. Official Methods of Analysis. Vol. 1. 18th ed. AOAC International).

2.6. Water Quality Analysis

Due to the volume of water samples, similar water locations from the same ranch during the same season were pooled to create a composite sample for source of natural sources of water. Water samples were sent to Weld County Water Quality Laboratories in Greeley, CO for livestock suitability basic water testing for Ca, Mg, pH, nitrates (NO₃-N), and sulfates (SO₄-S).

2.7. Statistical Analysis

Descriptive statistics were reported utilizing R 4.2.2 (R Core Team, 2021), with individual animal tissue as the observational unit. Descriptive statistics were calculated for all variables of interest and summarized by their means, standard deviation, minimum, mode, and maximum.

2.7.1. Scoping Review Weighted Mean

Utilizing the previous scoping review, weighted means were calculated utilizing R 4.2.2 (R Core Team, 2021). Exclusion criteria of articles' data not used for final weighted mean calculation included 1) articles' data not including specification of units and/or units were based upon a wet or dry weight basis, 2) articles' data specifying that animals sampled were in any way unhealthy or abnormal and, 3) articles' data not specifying the final sample number of animals for any given element and/or tissue. All articles' data chosen after exclusions were discarded were then divided by subgroups of element of interest and then by tissue investigated. After conversion of units to like units of the following study's units, each subgroup of data was then calculated for a weighted mean by multiplying each data point (concentrations of element) by its corresponding weight (sample number), summing these products, and then dividing the result by the total of the weights (total sample number of all article's data). Final weighted means are presented in the following tables were noted, and single articles' data is noted when present.

3. Results and Discussion

3.1. Population Summary

Farmed American bison were sampled from a total of 8 location: Colorado (n = 1), Idaho (n = 1), New Mexico (n = 1), South Dakota (n = 1), Montana (n = 1), and Nebraska (n = 3). The sample population included heifers under three years (n = 248), bulls under three years (n = 290), cows over 3 years (n = 181) and bulls over 3 years (n = 22). No calves were sampled within the study. From each bison, blood (plasma and serum), liver, kidney, and muscle were collected. In total, 741 bison were sampled. When investigating predominant feed types, the majority of bison were grain-fed (n = 402); there were 238 grass-fed bison samples. Due to limit of communication for some ranches, some bison could not be recorded for predominant feed type data (n = 101). The average live weight of all bison was 441.74 kg and total average hot carcass weight was 255.64 kg (**Table 2.1**).

Table 2.1. Average live weight and hot carcass weight of bison sampled at slaughter facilities

Sex Class	n	Live Wt. Mean (kg)	Live Weight SD	Hot Carcass Wt. Mean (kg)	Hot Carcass SD
Bull (<3 years)	290	461.349	43.06	278.40	27.69
Heifer (<3 years)	248	419.02	44.96	248.68	32.97
Cow (>3 years)	181	413.74	53.38	216.14	31.68
Bull (>3 years)	22	635.10	158.62	356.26	93.86
Grand Total	741	441.74	67.22	255.64	45.39

3.2. Feed Summary

Feed was sampled from three ranch locations; Nebraska, Montana, and South Dakota (**Table 2.2**). Although the intended sampling schedule was to visit locations each time within a specified meteorological season, complications of travel disrupted balanced sampling (**Table 2.3**). Nebraska was the only location that was able to be sampled in all seasons, while South

Dakota covered spring, summer, and winter. Montana had the least number of visits, with one in early spring, and the other in late summer. Feedlot feed samples were sampled at every location visited, and only one pasture sample could not be collected from the Montana location due to the large amount of snow. In the feedlot, the common diet was ad libitum whole corn, alfalfa hay, and grass hay: because there was no specific balanced diet, “feedlot” in **Table 2.2** and **Table 2.3** is an average of these three components. Pasture samples were generalized clippings from pasture currently being grazed at the time of collection. Multiple pasture locations were chosen at each location visit, but “pasture” in **Table 2.2** and **Table 2.3** is an average of all pasture samples from a given season or from a given location respectively. Both “feedlot” and “pasture” do not include any supplemented minerals, typically distributed by way of a salt or mineral block. All feedlot pens had access to at least one salt and/or mineral block, but access for pasture or grass-fed animals was varied. Overall intake of feedstuffs was not collected for this study but is research that could be collected in the future to gain a better insight into the consumptions of different minerals and vitamins of these farmed bison.

3.3. Water Summary

Water was sampled from three major ranch locations: Nebraska, Montana, and South Dakota (**Table 2.4**). Although the intended sampling schedule was to visit locations each time within a specified meteorological season, complications of travel disrupted balanced sampling (**Table 2.5**). **Table 2.4** and **Table 2.5** averages all water sampled over location and over season, respectively. Therefore, it includes wells and natural sources of water. All feedlot water sampled came from well sources, while pastures included a variety of water sources, from wells (solar and windmill) to natural ponds and springs. It is worth noting that the South Dakota location included some artesian well sources that could have attributed to higher amounts of sulfates and

nitrates than other sources of water. Assessment of water sources is essential for understanding current animal intake of minerals; however, intake was not an objective of this study so conclusions cannot be stipulated from just water data. Future research should include contents of minerals within water sources of bison in conjunction with intake in order to better understand the concentrations of minerals being consumed through water sources alone.

Table 2.2. Mineral content of sampled feed from bison ranch locations¹

Location & Feed Type	n	Ca Mean	Ca SD	Cl Mean	Cl SD	Co Mean	Co SD	Cu Mean	Cu SD	Fe Mean	Fe SD	K Mean	K SD	Mg Mean	Mg SD
Nebraska	47	5110.40	5121.27	4623.34	1699.54	1.90	1.34	3.76	1.44	164.63	201.63	10952.63	5537.60	1785.74	449.79
Feedlot	26	6349.92	6672.65	4372.34	2220.14	0.88	0.89	4.16	1.78	249.29	241.06	11865.08	7362.56	1745.77	560.33
Pasture	21	3575.77	444.41	4934.09	546.70	3.17	0.32	3.27	0.59	59.81	3.59	9822.92	589.88	1835.24	261.15
Montana	15	4580.39	4036.54	4946.41	2064.16	1.27	1.34	3.96	1.63	187.80	218.78	10973.92	6066.64	1529.19	435.87
Feedlot	11	4796.84	4755.13	4890.92	2431.50	0.50	0.15	4.04	1.92	233.73	241.46	11534.42	7085.87	1401.06	422.65
Pasture	4	3985.15	148.51	5099.01	366.02	3.41	0.24	3.75	0.17	61.48	4.59	9432.56	260.44	1881.56	255.69
South Dakota	18	5303.94	4832.48	4768.95	1930.06	1.24	1.20	4.05	1.84	233.09	275.77	11519.10	6385.28	1751.95	495.75
Feedlot	13	5957.78	5597.33	4744.82	2294.46	0.54	0.13	4.41	2.04	300.05	300.41	12125.45	7498.69	1717.34	563.92
Pasture	5	3603.96	507.76	4831.68	177.11	3.05	0.55	3.13	0.58	58.98	2.64	9942.56	536.04	1841.95	276.57
Grand Total	80	5054.57	4821.11	4716.67	1803.99	1.63	1.33	3.87	1.56	184.38	222.02	11084.08	5762.57	1730.04	462.57
Location & Feed Type	n	Mn Mean	Mn SD	Mo Mean	Mo SD	Na Mean	Na SD	P Mean	P SD	S Mean	S SD	Se Mean	Se SD	Zn Mean	Zn SD
Nebraska	47	51.96	22.94	1.17	0.72	713.88	599.96	1936.09	921.56	1939.26	1468.26	0.79	0.19	21.74	4.16
Feedlot	26	41.97	26.70	0.73	0.70	804.77	800.30	2328.25	1093.78	2334.37	1896.24	0.66	0.14	21.44	3.94
Pasture	21	64.33	5.37	1.73	0.10	601.34	56.92	1450.55	102.02	1450.07	97.25	0.95	0.07	22.10	4.50
Montana	15	51.50	27.17	1.12	0.73	557.41	649.91	1948.61	1000.36	1733.44	1363.11	0.69	0.25	23.51	4.60
Feedlot	11	49.08	31.72	0.88	0.71	528.52	765.92	2130.44	1122.39	1837.93	1597.87	0.61	0.23	21.85	4.08
Pasture	4	58.16	3.00	1.78	0.08	636.88	64.94	1448.58	127.15	1446.08	101.02	0.93	0.10	28.06	2.43
South Dakota	18	49.27	25.93	1.00	0.80	783.13	738.54	2176.96	1125.97	2035.77	1563.35	0.73	0.19	22.74	4.34
Feedlot	13	43.89	28.75	0.70	0.74	856.87	865.94	2431.75	1241.50	2263.92	1805.04	0.65	0.16	22.70	4.83
Pasture	5	63.27	6.33	1.77	0.11	591.42	70.43	1514.52	68.71	1442.59	61.01	0.92	0.05	22.86	3.19
Grand Total	80	51.27	24.15	1.12	0.74	700.12	638.25	1992.63	977.08	1922.38	1456.15	0.76	0.20	22.30	4.29

¹All averages given on mg/kg D.W.

Table 2.3. Seasonal average mineral content of sampled feed from all bison ranches¹

Season & Feed Type	n	Ca Mean	Ca SD	Cl Mean	Cl SD	Co Mean	Co SD	Cu Mean	Cu SD	Fe Mean	Fe SD	K Mean	K SD	Mg Mean	Mg SD
Spring	33	5304.55	5497.63	4581.96	1581.35	1.47	1.28	3.91	1.62	195.11	231.49	11152.56	5248.43	1759.24	467.38
Feedlot	23	6138.64	6441.61	4430.33	1858.95	0.76	0.74	4.20	1.86	254.16	256.73	11674.34	6243.42	1701.75	532.58
Pasture	10	3386.14	406.36	4930.69	500.08	3.12	0.37	3.24	0.47	59.29	2.47	9952.47	600.11	1891.46	235.51
Summer	29	4498.34	3661.72	4909.00	1922.84	1.72	1.38	3.78	1.49	164.56	200.37	10792.99	5688.32	1647.53	430.09
Feedlot	16	5077.75	4909.19	4844.35	2585.18	0.53	0.15	4.16	1.87	249.47	240.36	11738.96	7620.63	1519.28	490.49
Pasture	13	3785.22	402.49	4988.58	510.55	3.20	0.36	3.32	0.65	60.05	3.77	9628.72	495.40	1805.38	286.31
Autumn	12	5322.95	4835.68	4705.12	2266.63	1.48	1.38	3.88	1.79	227.34	275.70	11634.64	7632.99	1819.96	558.63
Feedlot	8	6177.50	5843.91	4607.18	2817.49	0.56	0.12	4.26	2.09	311.67	308.32	12673.79	9365.74	1752.03	667.45
Pasture	4	3613.86	460.87	4900.99	488.40	3.34	0.23	3.11	0.61	58.67	3.58	9556.35	563.11	1955.83	260.44
Winter	6	5831.36	6646.40	4551.15	1743.58	2.40	1.40	4.00	1.34	135.24	182.95	11013.20	6143.87	1788.36	437.79
Feedlot	3	7820.48	9915.34	4299.65	2678.04	1.67	1.72	4.25	2.04	207.56	260.68	11759.38	9619.60	1887.39	661.88
Pasture	3	3842.24	502.83	4802.64	488.37	3.12	0.59	3.76	0.37	62.91	5.60	10267.02	401.05	1689.32	107.88
Grand Total	80	5054.57	4821.11	4716.67	1803.99	1.63	1.33	3.87	1.56	184.38	222.02	11084.08	5762.57	1730.04	462.57
Season & Feed Type	n	Mn Mean	Mn SD	Mo Mean	Mo SD	Na Mean	Na SD	P Mean	P SD	S Mean	S SD	Se Mean	Se SD	Zn Mean	Zn SD
Spring	33	51.61	23.44	1.12	0.73	742.18	702.02	2028.96	992.57	1979.32	1504.12	0.76	0.18	22.28	4.14
Feedlot	23	46.71	26.50	0.85	0.73	800.34	838.60	2271.31	1107.70	2207.90	1762.88	0.68	0.16	22.26	4.36
Pasture	10	62.86	5.91	1.73	0.12	608.40	68.48	1471.56	90.84	1453.58	81.47	0.94	0.07	22.35	3.83
Summer	29	52.95	24.90	1.21	0.73	653.11	630.03	1931.59	1009.98	1773.72	1405.74	0.76	0.23	22.04	4.72
Feedlot	16	45.78	31.78	0.75	0.69	684.25	858.07	2309.05	1246.88	2062.25	1866.49	0.61	0.20	20.94	4.31
Pasture	13	61.77	5.63	1.77	0.06	614.78	54.35	1467.02	113.89	1418.61	92.65	0.95	0.07	23.39	5.02
Autumn	12	46.04	26.51	0.90	0.77	689.54	641.19	2169.71	1048.88	2013.61	1421.63	0.71	0.20	21.96	3.86
Feedlot	8	36.41	27.92	0.51	0.65	754.58	793.50	2545.26	1112.83	2281.14	1711.02	0.60	0.13	22.10	3.28
Pasture	4	65.31	4.00	1.66	0.12	559.45	66.77	1418.61	126.63	1478.55	82.78	0.93	0.07	21.68	5.42
Winter	6	51.79	24.41	1.19	0.82	717.27	360.32	1733.73	678.31	2145.29	1811.33	0.83	0.18	24.26	4.27
Feedlot	3	34.53	24.40	0.66	0.90	828.26	535.43	2011.77	956.77	2771.62	2648.55	0.70	0.17	23.05	5.22
Pasture	3	69.05	1.18	1.73	0.09	606.27	30.46	1455.70	54.32	1518.97	103.03	0.95	0.07	25.46	3.74
Grand Total	80	51.27	24.15	1.12	0.74	700.12	638.25	1992.63	977.08	1922.38	1456.15	0.76	0.20	22.30	4.29

¹All averages given on mg/kg D.W.

Table 2.4. Water quality results by location of origin of bison sampled

Location ¹	n	Ca Mean (ppm)	Ca SD	Mg Mean (ppm)	Mg SD	pH Mean (SI)	pH SD	SO ⁴ -S Mean (ppm)	SO ⁴ -S SD	NO ³ -N Mean (ppm)	NO ³ -N SD
MT	6	11.98	5.58	8.80	6.80	8.31	0.30	9.80	6.94	<0.1	<0.1
NE	11	17.42	12.92	2.93	2.57	7.55	0.28	2.43	1.07	1.42	1.00
SD	25	91.43	87.08	27.88	21.82	7.93	0.33	273.06	224.92	2.77	<0.1
Grand Total	42	36.03	55.41	10.30	15.56	7.76	0.40	74.36	163.41	1.51	1.02

¹MT: Montana, NE: Nebraska, SD: South Dakota – Average of all water sampled over location

Table 2.5. Water quality results by season sampled

Season ¹	n	Ca Mean (ppm)	Ca SD	Mg Mean (ppm)	Mg SD	pH Mean (SI)	pH SD	SO ⁴ -S Mean (ppm)	SO ⁴ -S SD	NO ³ -N Mean (ppm)	NO ³ -N SD
Fall	6	25.14	16.36	3.39	0.94	7.38	0.27	16.21	32.81	2.92	0.17
Spring	17	45.42	80.39	13.90	20.14	7.88	0.48	104.45	210.71	1.59	0.79
Summer	16	32.03	33.42	10.66	13.42	7.81	0.30	77.77	147.75	1.24	1.14
Winter	3	25.87	28.50	1.87	0.88	7.62	0.26	1.98	0.35	0.46	0.25
Grand Total	42	36.03	55.41	10.30	15.56	7.76	0.40	74.36	163.41	1.51	1.02

¹All water sampled average over season

3.4. Tissue Mineral and Vitamin Concentrations

Table 2.6 through Table 2.23 represent every mineral and vitamin investigated for each tissue type (liver, kidney, muscle, plasma, and serum). Each table is divided first by tissue, then by sex, and then lastly by age within sex. Reference ranges from normal ranges of cattle are given from at least one published source for comparison. Due to either missed collection of samples at slaughter facilities or contaminated samples due to laboratory errors, total samples utilized for each category are stated in each table and deviate from the total 741 bison sampled.

3.4.1. *Vitamin A*

Table 2.6 presents data showing that average liver values fall within the normal ranges established by Puls (1994) for beef cattle. While maximum values also align with these ranges, minimum values are approximately 10,500 mg/kg D.W. lower than the lower end of Puls' range. Vitamin A, typically sourced from lush green pastures, is effectively stored in the liver of ruminant animals. During periods of reduced intake, vitamin A can be mobilized to meet physiological needs for two to four months without visible signs of deficiency (Becka and Hall, 2023; Wagner et al., 2023). Kidney data averages are consistent with USDA (2024) reference values for beef cattle. However, muscle tissue data averages are approximately 2.0 µg/100 g D.W. lower than the weighted averages reported in the scoping review, aligning more closely with minimum reported values rather than mean values. Excessive dietary vitamin A intake can negatively impact intramuscular fat deposition in cattle (Becka and Hall, 2023). Studies on bison meat have revealed significant differences in vitamin A concentrations between grain-fed and grass-fed diets, as well as variations among different meat cuts (Driskell et al., 2004; Galbraith et al., 2006). Serum and plasma vitamin A averages fall within the ranges outlined by Puls (1994). However, the maximum plasma vitamin A concentration exceeded the average levels by more than twofold. Overall, vitamin A values from the study aligned with pre-established normal ranges of beef cattle for most tissue types.

Table 2.6. Descriptive statistics of Vitamin A concentrations within various tissue types across sexes and ages of bison

Vitamin A								
Tissue	Sex	Age	n	Mean	SD	Mode	Min	Max
Liver <i>ug/100g</i> <i>D.W.</i>	Female	<3	247	31248.50	8881.80	30743.15	15252.53	51191.92
		>3	178	32134.87	9957.85	31663.78	15223.67	51666.67
		All Ages	425	31619.73	9346.38	31139.97	15223.67	51666.67
	Male	<3	278	30089.49	9196.46	29196.97	15252.53	51353.54
		>3	22	36722.94	7960.58	35439.39	22301.59	50141.41
		All Ages	300	30575.94	9262.99	29893.94	15252.53	51353.54
	Total			725	31187.82	9319.76	30668.79	15223.67
Reference values							30000.00-70000.00**	
Kidney <i>ug/100g</i> <i>D.W.</i>	Female	<3	246	391.86	60.62	391.03	258.59	523.16
		>3	171	405.13	63.15	400.00	310.31	522.11
		All Ages	417	397.30	61.94	393.68	258.59	523.16
	Male	<3	286	415.54	62.25	419.79	287.80	523.16
		>3	22	406.58	62.32	406.70	319.59	505.15
		All Ages	308	414.90	62.19	419.27	287.80	523.16
	Total			725	404.78	62.61	408.16	258.59
Reference values			419.00***					
Muscle <i>ug/100g</i> <i>D.W.</i>	Female	<3	245	2.23	0.98	2.21	0.49	5.94
		>3	178	2.14	1.13	1.97	0.44	5.26
		All Ages	423	2.19	1.05	2.11	0.44	5.94
	Male	<3	282	2.31	1.14	2.20	0.46	4.96
		>3	22	2.48	1.13	2.25	0.69	4.75
		All Ages	304	2.32	1.14	2.20	0.46	4.96
	Total			727	2.25	1.09	2.15	0.44
Reference values			4.58*					
Serum <i>ng/ml</i>	Female	<3	242	58.89	9.58	58.18	38.82	81.86
		>3	166	59.27	10.27	58.63	35.81	81.21
		All Ages	408	59.05	9.86	58.43	35.81	81.86
	Male	<3	286	59.16	9.13	59.15	40.84	82.12
		>3	21	57.52	9.61	54.25	44.61	81.40
		All Ages	307	59.05	9.15	58.93	40.84	82.12
	Total			715	59.05	9.56	58.65	35.81
Reference values							30.00-80.00**	
Plasma <i>ng/ml</i>	Female	<3	246	72.47	37.67	63.05	19.32	206.99
		>3	169	74.79	36.86	68.72	18.05	167.99
		All Ages	415	73.41	37.31	66.11	18.05	206.99
	Male	<3	290	72.49	38.50	64.26	18.83	220.49
		>3	22	72.67	45.85	65.91	22.82	206.82
		All Ages	312	72.50	38.98	64.26	18.83	220.49
	Total			727	73.02	38.01	65.31	18.05
Reference values							25.00-80.00**	

¹ Concentrations represented on a dry weight basis (D.W.) where indicated.

² Age in years (<3 years and >3 years). "All ages" indicates all ages of bison within specified sex.

* Weighted means calculated from scoping review, **acc. Puls, 1994, ***acc. USDA, 2024

3.4.2. *Vitamin E (α -tocopherol)*

Vitamin E, primarily derived from plant-based tocopherols and tocotrienols, is represented most biologically by α -tocopherol, a key compound in feeds and forages (McDowell, 2006; Becka and Hall, 2023). **Table 2.7** presents liver data averages that align closely with the lower end of the normal ranges for beef cattle established by Puls (1994). Kidney total α -tocopherol averages fell within the ranges defined by Puls (1994), while muscle tissue averages were approximately 0.30 mg/100g lower than the weighted averages reported in the scoping review. Among the vitamins studied in the bison scoping review, α -tocopherol (vitamin E) received the most attention, particularly concerning its concentrations in meat and its role in color stability. A comparison between bison and beef by Galbraith et al. (2016) revealed that bison meat exhibited higher concentrations of α -tocopherol; however, it did not demonstrate superior color stability for retail cuts. Additionally, a study contrasting grass-fed and grain-fed bison found no significant differences in α -tocopherol concentrations, while another investigation noted no significant differences in α -tocopherol concentrations among various bison meat cuts (Marchello et al., 1998; Driskell et al., 2004). Lastly, average serum and plasma α -tocopherol concentrations were within the ranges specified by Puls (1994). In all, vitamin E α -tocopherol values from the study align with pre-established normal ranges of beef cattle for most tissue types.

Table 2.7. Descriptive statistics of Vitamin E (α -tocopherol) concentrations within various tissue types across sexes and ages of bison

Vitamin E (α -tocopherol)								
Tissue	Sex	Age	n	Mean	SD	Mode	Min	Max
Liver <i>mg/100g D.W.</i>	Female	<3	247	1.19	0.87	0.90	0.30	4.52
		>3	178	0.98	0.59	0.84	0.20	3.28
		All Ages	425	1.10	0.77	0.88	0.20	4.52
	Male	<3	278	1.19	0.70	1.06	0.26	3.44
		>3	22	1.02	0.56	1.01	0.30	1.98
		All Ages	300	1.18	0.69	1.06	0.26	3.44
	Total			725	1.13	0.74	0.93	0.20
Reference values				1.20 - 3.00**				
Kidney <i>mg/100g D.W.</i>	Female	<3	247	0.41	0.12	0.40	0.15	0.75
		>3	177	0.44	0.13	0.43	0.15	0.76
		All Ages	424	0.42	0.12	0.41	0.15	0.76
	Male	<3	289	0.45	0.12	0.45	0.19	0.75
		>3	22	0.44	0.12	0.43	0.23	0.71
		All Ages	311	0.45	0.12	0.44	0.19	0.75
	Total			735	0.43	0.12	0.43	0.15
Reference values				0.20 - 0.50***				
Muscle <i>mg/100g D.W.</i>	Female	<3	245	0.24	0.07	0.24	0.09	0.48
		>3	178	0.23	0.08	0.22	0.08	0.43
		All Ages	423	0.24	0.08	0.23	0.08	0.48
	Male	<3	282	0.25	0.08	0.24	0.09	0.43
		>3	22	0.26	0.07	0.24	0.11	0.40
		All Ages	304	0.25	0.08	0.24	0.09	0.43
	Total			727	0.24	0.08	0.24	0.08
Reference values				0.59*				
Serum <i>ug/ml</i>	Female	<3	240	1.69	0.85	1.42	0.60	4.78
		>3	166	1.59	0.72	1.37	0.61	3.65
		All Ages	406	1.65	0.80	1.41	0.60	4.78
	Male	<3	283	1.65	0.83	1.35	0.59	5.04
		>3	21	1.81	0.85	1.68	0.63	3.47
		All Ages	304	1.66	0.83	1.37	0.59	5.04
	Total			710	1.65	0.81	1.39	0.59
Reference values				1.25 - 10.00**				
Plasma <i>ug/ml</i>	Female	<3	243	2.05	0.82	1.91	0.63	4.15
		>3	169	1.98	0.72	1.86	0.83	4.05
		All Ages	412	2.02	0.78	1.89	0.63	4.15
	Male	<3	290	2.08	0.80	2.01	0.64	3.96
		>3	22	2.08	0.76	2.03	0.70	3.30
		All Ages	312	2.08	0.79	2.01	0.64	3.96
	Total			724	2.05	0.78	1.93	0.63
Reference values				1.25 - 10.00**				

¹ Concentrations represented on a dry weight basis (D.W.) where indicated.

² Age in years (<3 years and >3 years). "All ages" indicates all ages of bison within specified sex.

* Weighted means calculated from scoping review, **acc. Puls, 1994, ***acc. NASEM, 2016

3.4.3. *Vitamin E (γ -tocopherol)*

Table 2.8 presents liver data averages within the normal range for beef cattle as reported by NASEM (2016), with maximum values also falling within this range. Kidney data averages, however, are slightly lower than the NASEM (2016) beef cattle range, while muscle tissue averages are numerically consistent across ages and sexes but approximately 0.05 mg/kg D.W. lower than the reference values from NASEM (2016). Research on Vitamin E (γ -tocopherol) in beef cattle is limited, with most studies focusing on its presence in milk from dairy cattle (Hidioglou, 1989). Investigating the role of γ -tocopherol in bison milk may provide valuable insights into its contribution to the growth and immunity development of bison calves (Hidioglou, 1989; Al Senaidy, 1996). Additionally, serum and plasma data averages align with the ranges specified by NASEM (2016), suggesting that γ -tocopherol levels in bison may be comparable to those observed in beef cattle.

Table 2.8. Descriptive statistics of Vitamin E (γ -tocopherol) concentrations within various tissue types across sexes and ages of bison

Vitamin E (γ -tocopherol)								
Tissue	Sex	Age	n	Mean	SD	Mode	Min	Max
Liver <i>mg/100g D.W.</i>	Female	<3	247	0.11	0.03	0.10	0.05	0.19
		>3	178	0.11	0.03	0.10	0.05	0.20
		All Ages	425	0.11	0.03	0.10	0.05	0.20
	Male	<3	278	0.10	0.03	0.09	0.05	0.20
		>3	22	0.12	0.04	0.12	0.05	0.19
		All Ages	300	0.10	0.03	0.10	0.05	0.20
	Total			725	0.11	0.03	0.10	0.05
Reference values						0.10 - 0.20*		
Kidney <i>mg/100g D.W.</i>	Female	<3	247	0.08	0.04	0.07	0.02	0.21
		>3	177	0.08	0.04	0.08	0.01	0.20
		All Ages	424	0.08	0.04	0.07	0.01	0.21
	Male	<3	289	0.09	0.04	0.08	0.01	0.21
		>3	22	0.08	0.04	0.07	0.02	0.17
		All Ages	311	0.09	0.04	0.08	0.01	0.21
	Total			735	0.08	0.04	0.08	0.01
Reference values						0.10 - 0.20*		
Muscle <i>mg/100g D.W.</i>	Female	<3	245	0.14	0.05	0.13	0.05	0.34
		>3	178	0.15	0.07	0.14	0.05	0.44
		All Ages	423	0.14	0.06	0.13	0.05	0.44
	Male	<3	282	0.14	0.06	0.12	0.06	0.36
		>3	22	0.12	0.03	0.13	0.06	0.20
		All Ages	304	0.14	0.06	0.12	0.06	0.36
	Total			727	0.14	0.06	0.13	0.05
Reference values						0.20 - 0.30*		
Serum <i>ng/ml</i>	Female	<3	240	26.75	19.05	22.88	2.51	88.62
		>3	166	28.33	19.54	26.11	3.29	83.15
		All Ages	406	27.39	19.24	23.52	2.51	88.62
	Male	<3	283	27.46	19.56	24.31	2.38	90.41
		>3	21	24.74	21.51	17.02	4.11	78.87
		All Ages	304	27.27	19.67	23.82	2.38	90.41
	Total			710	27.34	19.41	23.61	2.38
Reference values						20.00 - 30.00*		
Plasma <i>ng/ml</i>	Female	<3	246	30.87	16.23	27.04	6.57	71.75
		>3	168	30.53	14.76	28.28	6.18	67.10
		All Ages	414	30.73	15.63	27.83	6.18	71.75
	Male	<3	287	30.62	15.14	27.76	6.31	73.83
		>3	22	35.57	16.62	37.51	7.92	70.41
		All Ages	309	30.97	15.28	27.96	6.31	73.83
	Total			723	30.83	15.47	27.84	6.18
Reference values						20.00 - 30.00*		

¹ Concentrations represented on a dry weight basis (D.W.) where indicated.

² Age in years (<3 years and >3 years). "All ages" indicates all ages of bison within specified sex.

* acc. NASEM, 2016

3.4.4. *Vitamin K*

Vitamin K is a water soluble vitamin, and is rarely supplemented to ruminant animals due to the capability of microorganisms within the rumen to produce required concentrations for the animal (O'Donovan, 1966; Wagner et al., 2023). **Table 2.9** shows liver ranges are wide and varied, but the average presented from Matschiner et al. (1967) is similar to the average of data with only a difference of 30 ug/100g dry weight. Kidney concentrations were below detectable limits, as well as serum concentrations. Muscle total averages were only marginally higher than average of cattle stated from Rødbotten et al. (2014). Although not many studies focus on vitamin K content in tissues of cattle, and even less studies focused in bison, research investigating stress of shipping and long-term handling research has begun to look into Vitamin K supplementation and outcomes in order to access potential boost to immunity and resilience to stress (McDowell, 2006; Wagner et al., 2023). In total, vitamin K values from the study are difficult to compare with pre-established normal ranges of beef cattle for most tissue types; However, concentrations are comparable to other bison research for liver and muscle.

Table 2.9. Descriptive statistics of Vitamin K concentrations within various tissue types across sexes and ages of bison

Vitamin K								
Tissue	Sex	Age	n	Mean	SD	Mode	Min	Max
Liver <i>ug/100g D.W.</i>	Female	<3	241	311.79	242.07	233.52	27.29	988.73
		>3	180	357.53	270.07	277.73	32.67	1066.11
		All Ages	421	331.35	255.12	250.92	27.29	1066.11
	Male	<3	282	248.43	239.29	137.65	8.22	1079.61
		>3	22	441.83	242.17	429.72	49.62	1043.31
		All Ages	304	262.43	244.30	150.12	8.22	1079.61
	Total			725	302.45	252.77	199.34	8.22
Reference values				270.00*				
Kidney <i>ug/100g D.W.</i>	Female	<3	246	BDL				
		>3	171					
		All Ages	417					
	Male	<3	286					
		>3	22					
		All Ages	308					
	Total							
Muscle <i>ug/100g D.W.</i>	Female	<3	245	1.79	0.58	1.75	0.63	4.01
		>3	178	1.72	0.61	1.68	0.59	3.40
		All Ages	423	1.76	0.59	1.72	0.59	4.01
	Male	<3	282	1.82	0.64	1.73	0.59	3.28
		>3	22	1.90	0.56	1.88	0.77	3.04
		All Ages	304	1.82	0.63	1.73	0.59	3.28
	Total			727	1.78	0.61	1.72	0.59
Reference values				3.60**				
Serum <i>ng/ml</i>	Female	<3	240	BDL				
		>3	166					
		All Ages	406					
	Male	<3	283					
		>3	21					
		All Ages	304					
	Total							
Plasma <i>ng/ml</i>	Female	<3	243	0.11	0.02	0.10	0.08	0.16
		>3	169	0.11	0.02	0.10	0.08	0.16
		All Ages	412	0.11	0.02	0.10	0.08	0.16
	Male	<3	290	0.11	0.02	0.10	0.08	0.16
		>3	22	0.11	0.02	0.10	0.08	0.16
		All Ages	312	0.11	0.02	0.10	0.08	0.16
	Total			724	0.11	0.02	0.10	0.08

¹ Concentrations represented on a dry weight basis (D.W.) where indicated.

² Age in years (<3 years and >3 years). “All ages” indicates all ages of bison within specified sex.

* acc. Matschiner et al., 1967, ** acc. Rødbotten et al., 2014

3.4.5. Calcium

Table 2.10 indicates that the mean liver calcium concentrations across all sampled animals are within the normal ranges for beef cattle, as referenced by Puls (1994). Despite a numeric difference of 200 mg/kg D.W. from the study's total average, the scoping review's weighted mean for liver calcium concentration remains consistent with Puls's ranges. Conversely, kidney calcium concentrations from the study's total animal averages exceeded the normal range and fell within the high and toxic classifications. However, high dietary calcium intake is typically only marginally harmful, potentially reducing feed intake and growth slightly as seen in cattle (Goff, 2000). Calcium concentrations depend on dietary availability and absorption efficiency in the lower gastrointestinal tract, which can vary significantly with diet composition. Low-quality wheat and forage-based diets tend to provide less bioavailable calcium compared to those supplemented with limestone or high-energy concentrates (Goff, 2000; DeGaris and Lean, 2008). The scoping review's weighted mean for kidney calcium concentrations in bison aligns more closely with this study's data than with beef cattle references. However, both the minimum and maximum values from the study exceeded the normal ranges for cattle kidneys (Puls, 1994). While age significantly influences calcium absorption—ranging from 60–70% in younger animals to 15–50% in adults—this study found no numerical differences related to age (Hansard et al., 1954). Muscle calcium content in bison was similar to a previous study by Doornenbal & Murray (1982), with only a small difference of 50 mg/kg D.W. compared to the scoping review's weighted mean. Differences in diet, such as grass-fed versus confinement systems, likely contribute to these variations, as higher forage diets are often lower in calcium (DeGaris and Lean, 2008; Becka and Hall, 2023). Serum and plasma calcium concentrations provide insight into bioavailable calcium and are particularly well-studied in

lactating animals like dairy cattle (Goff, 2000; DeGaris and Lean, 2008). The study's total animal averages for plasma and serum calcium concentrations fell within the normal ranges reported by Puls (1994), as did the weighted means for bison plasma and serum calcium concentrations in the scoping review. In summary, the calcium concentrations observed in bison tissues largely align with the established ranges for beef cattle (Puls, 1994), with some variations likely influenced by dietary and environmental factors.

Table 2.10. Descriptive statistics of calcium concentrations within various tissue types across sexes and ages of bison

Calcium									
Tissue	Sex	Age	n	Mean	SD	Mode	Min	Max	
Liver mg/kg <i>D.W.</i>	Female	<3	247	324.20	84.05	332.63	130.53	461.76	
		>3	180	323.99	86.53	332.64	129.47	459.70	
		All Ages	427	324.11	85.01	332.63	129.47	461.76	
	Male	<3	278	313.54	91.86	321.11	130.78	459.70	
		>3	21	337.88	97.92	365.18	134.74	459.70	
		All Ages	299	315.25	92.34	322.17	130.78	459.70	
	Total			726	320.46	88.14	327.05	129.47	461.76
	Reference values				552.95*			100.00 - 666.67**	
Kidney mg/kg <i>D.W.</i>	Female	<3	246	2445.76	701.82	2416.28	1311.58	3807.28	
		>3	158	2471.02	746.95	2544.65	1337.90	3794.33	
		All Ages	404	2455.64	718.99	2446.45	1311.58	3807.28	
	Male	<3	284	2489.35	729.11	2495.93	1346.32	3886.85	
		>3	22	2488.77	826.79	2491.96	1408.31	3582.27	
		All Ages	306	2489.31	735.07	2495.93	1346.32	3886.85	
	Total			710	2470.15	725.64	2471.80	1311.58	3886.85
	Reference values				2043.63*			225.00 - 1000.00**	
Muscle mg/kg <i>D.W.</i>	Female	<3	245	160.67	48.69	161.86	73.64	267.01	
		>3	175	166.31	49.99	166.67	73.64	258.76	
		All Ages	420	163.02	49.26	164.47	73.64	267.01	
	Male	<3	281	157.88	49.52	156.99	72.92	263.92	
		>3	22	150.40	43.65	153.61	76.40	243.30	
		All Ages	303	157.34	49.09	156.48	72.92	263.92	
	Total			723	160.64	49.24	160.82	72.92	267.01
	Reference values				200.92*				
				154.20***					
Serum mg/l	Female	<3	248	107.88	26.93	105.46	64.06	181.25	
		>3	171	107.63	27.00	104.35	63.28	187.50	
		All Ages	419	107.78	26.93	104.95	63.28	187.50	
	Male	<3	286	107.11	24.80	103.59	62.50	182.81	
		>3	22	104.74	22.02	100.65	64.90	141.67	
		All Ages	308	106.94	24.59	103.05	62.50	182.81	
	Total			727	107.42	25.95	104.17	62.50	187.50
	Reference values				82.80*			80.00 - 110.00**	
Plasma mg/l	Female	<3	248	126.03	29.15	121.02	77.81	207.56	
		>3	172	129.51	31.98	128.02	81.13	222.22	
		All Ages	420	127.46	30.35	122.77	77.81	222.22	
	Male	<3	289	131.77	30.57	125.23	76.43	218.52	
		>3	22	127.05	35.80	115.13	82.76	195.65	
		All Ages	311	131.44	30.93	125.00	76.43	218.52	
	Total			731	129.15	30.64	123.02	76.43	222.22
	Reference values							80.00 - 110.00**	

¹ Concentrations represented on a dry weight basis (D.W.) where indicated.

² Age in years (<3 years and >3 years). "All ages" indicates all ages of bison within specified sex.

* acc. Scoping review weighted means, ** acc. Puls, 1994, *** acc. Doornenbal & Murray, 1982

3.4.6. Cobalt

Cobalt is an essential dietary component for ruminants, playing a critical role in the synthesis of vitamin B12 by ruminal microorganisms. The cobalt status of animals can be assessed through its concentrations in the liver and kidney (Tiffany and Spears, 2005). As shown in **Table 2.11**, the average liver cobalt concentration in this study aligns with the reference ranges for beef cattle established by Puls (1994), with both minimum and maximum values also falling within these ranges. Research by Durkalec et al. (2018), which investigated European bison across various herd locations, reported no significant differences in cobalt concentrations between wild and captive populations within the liver, though their values were slightly lower than those referenced by Puls (1994). For the kidney, the mean cobalt concentration is comparable to the weighted averages derived from the scoping review of bison studies. These findings are consistent with the kidney cobalt concentrations observed in this study. Muscle cobalt concentrations in this study are within the reference ranges for cattle provided by González-Montaña (2020), although the minimum and maximum values slightly deviate from these benchmarks. Similarly, serum cobalt concentrations examined by Klich et al. (2021) in European bison were found to be marginally lower than cattle reference values. In this study, serum concentrations also fall below Puls's (1994) reference ranges, with both plasma and serum values located at the lower end of the spectrum. The lower serum and plasma cobalt concentrations warrant further investigation into potential cobalt or vitamin B12 deficiencies. However, as dietary intake significantly influences cobalt availability, future studies should examine cobalt concentrations in feedstuffs and overall dietary composition (Tiffany et al., 2006; Klich et al., 2021).

Table 2.11. Descriptive statistics of cobalt concentrations within various tissue types across sexes and ages of bison

Cobalt								
Tissue	Sex	Age	n	Mean	SD	Mode	Min	Max
Liver <i>mg/kg</i> <i>D.W.</i>	Female	<3	248	0.53	0.39	0.43	0.09	2.22
		>3	180	0.47	0.26	0.41	0.09	1.95
		All Ages	428	0.51	0.34	0.42	0.09	2.22
	Male	<3	280	0.50	0.36	0.40	0.07	2.20
		>3	22	0.41	0.16	0.38	0.17	0.79
		All Ages	302	0.49	0.35	0.40	0.07	2.20
	Total			730	0.50	0.34	0.42	0.07
Reference values				0.22*			0.07 - 3.33**	
Kidney <i>mg/kg</i> <i>D.W.</i>	Female	<3	244	0.25	0.15	0.22	0.01	0.64
		>3	168	0.23	0.15	0.20	0.02	0.61
		All Ages	412	0.24	0.15	0.21	0.01	0.64
	Male	<3	284	0.24	0.14	0.21	0.02	0.62
		>3	21	0.25	0.15	0.27	0.02	0.47
		All Ages	305	0.24	0.14	0.21	0.02	0.62
	Total			717	0.24	0.15	0.21	0.01
Reference values				0.36**				
Muscle <i>mg/kg</i> <i>D.W.</i>	Female	<3	244	0.02	0.02	0.01	0.001	0.12
		>3	174	0.01	0.02	0.01	0.001	0.09
		All Ages	418	0.02	0.02	0.01	0.001	0.12
	Male	<3	282	0.02	0.02	0.01	0.001	0.10
		>3	22	0.01	0.01	0.01	0.001	0.06
		All Ages	304	0.02	0.02	0.01	0.001	0.10
	Total			722	0.02	0.02	0.01	0.001
Reference values							0.004 - 0.08***	
Serum <i>ug/l</i>	Female	<3	247	0.49	0.38	0.38	0.02	1.65
		>3	171	0.54	0.44	0.42	0.02	1.59
		All Ages	418	0.51	0.40	0.39	0.02	1.65
	Male	<3	286	0.55	0.43	0.47	0.02	1.75
		>3	22	0.58	0.42	0.56	0.05	1.39
		All Ages	308	0.55	0.43	0.47	0.02	1.75
	Total			726	0.53	0.41	0.42	0.02
Reference values							0.40 - 0.90**	
Plasma <i>ug/l</i>	Female	<3	248	1.43	0.71	1.36	0.26	3.12
		>3	172	1.35	0.63	1.39	0.23	2.90
		All Ages	420	1.40	0.68	1.37	0.23	3.12
	Male	<3	288	1.73	6.89	1.35	0.27	1.18
		>3	22	1.28	0.70	1.15	0.29	2.53
		All Ages	310	1.70	6.64	1.35	0.27	1.18
	Total			730	1.52	4.36	1.36	0.23
Reference values							0.90 - 15.0**	

¹ Concentrations represented on a dry weight basis (D.W.) where indicated.

² Age in years (<3 years and >3 years). "All ages" indicates all ages of bison within specified sex.

* acc. Scoping review weighted means, ** acc. Puls, 1994, *** acc. Jose-Ramiro et al., 2020

3.4.7. Chromium

Chromium concentrations and status in animals remain poorly understood and under-researched (Wagner et al., 2023). Chromium's primary function in mammals is to modulate the effects of insulin, yet no standardized sampling method exists for reliably determining an animal's chromium status (NASEM, 2016). **Table 2.12** demonstrates that the average liver chromium concentrations across all sampled animals align closely with ranges reported by Puls (1994), with only the minimum values slightly lower than these established normal ranges for cattle. The weighted mean concentrations from the scoping review also fall within the range defined by Puls (1994), exceeding the study's total animal liver chromium average by only 0.20–0.30 mg/kg dry weight. Research by Durkalec et al. (2018) on European bison revealed significantly higher chromium concentrations in the livers of wild herds compared to captive populations, likely attributed to the consumption of chromium-rich wild forages. The total average chromium concentrations in kidney and muscle samples were at the lower end of the ranges described by Puls (1994), with minimum values falling below these thresholds. Additionally, studies in beef cattle suggest chromium serum may serve as an indicator of stress or trauma, with reduced chromium concentrations associated with high-stress scenarios (Kegley et al., 1997; Spears, 2000). Serum and plasma chromium levels from the data also correspond to Puls's ranges but exhibit lower minimum values. Chromium's specific roles and mechanisms in ruminants are poorly understood, emphasizing the need to first investigate its functionality in other animal models to establish foundational knowledge before advancing research specific to bison.

Table 2.12. Descriptive statistics of chromium concentrations within various tissue types across sexes and ages of bison

Chromium									
Tissue	Sex	Age	n	Mean	SD	Mode	Min	Max	
Liver mg/kg D.W.	Female	<3	248	0.40	0.19	0.35	0.12	1.16	
		>3	180	0.39	0.17	0.37	0.12	1.24	
		All Ages	428	0.40	0.18	0.35	0.12	1.24	
	Male	<3	281	0.40	0.19	0.36	0.12	1.16	
		>3	22	0.37	0.16	0.35	0.18	0.83	
		All Ages	303	0.40	0.19	0.36	0.12	1.16	
	Total			731	0.40	0.19	0.35	0.12	1.24
	Reference values				0.67*			0.13 - 12.67**	
Kidney mg/kg D.W.	Female	<3	244	0.26	0.21	0.23	0.04	1.80	
		>3	168	0.23	0.16	0.22	0.04	1.87	
		All Ages	412	0.25	0.19	0.23	0.04	1.87	
	Male	<3	284	0.24	0.16	0.24	0.04	1.68	
		>3	21	0.31	0.35	0.29	0.06	1.78	
		All Ages	305	0.25	0.18	0.24	0.04	1.78	
	Total			717	0.25	0.19	0.23	0.04	1.87
	Reference values							0.25 - 3.10**	
Muscle mg/kg D.W.	Female	<3	245	0.21	0.16	0.18	0.01	0.71	
		>3	175	0.20	0.15	0.15	0.01	0.71	
		All Ages	420	0.21	0.16	0.17	0.01	0.71	
	Male	<3	282	0.20	0.15	0.17	0.01	0.72	
		>3	22	0.24	0.17	0.20	0.01	0.72	
		All Ages	304	0.21	0.15	0.17	0.01	0.72	
	Total			724	0.21	0.15	0.17	0.01	0.72
	Reference values							0.40 - 0.80**	
Serum ug/l	Female	<3	2	0.25	0.08	0.25	0.19	0.31	
		>3	0	NA	NA	NA	NA	NA	
		All Ages	2	0.25	0.08	0.25	0.19	0.31	
	Male	<3	7	0.19	0.08	0.21	0.02	0.25	
		>3	1	0.27	NA	0.27	0.27	0.27	
		All Ages	8	0.20	0.08	0.22	0.02	0.27	
	Total			10	0.21	0.08	0.22	0.02	0.31
	Reference values							0.25 - 0.30**	
Plasma ug/l	Female	<3	3	0.20	0.05	0.21	0.15	0.24	
		>3	1	0.11	NA	0.11	0.11	0.11	
		All Ages	4	0.18	0.06	0.18	0.11	0.24	
	Male	<3	4	0.19	0.10	0.18	0.09	0.31	
		>3	0	NA	NA	NA	NA	NA	
		All Ages	4	0.19	0.10	0.18	0.09	0.31	
	Total			8	0.18	0.07	0.18	0.09	0.31
	Reference values							0.25 - 0.30**	

¹ Concentrations represented on a dry weight basis (D.W.) where indicated.

² Age in years (<3 years and >3 years). "All ages" indicates all ages of bison within specified sex.

* acc. Scoping review weighted means, ** acc. Puls, 1994

3.4.8. *Copper*

Copper is essential for numerous enzymatic processes, including those involved in energy production, protein and lipid metabolism, and storage, with status typically assessed through liver copper concentrations (NASEM, 2016). **Table 2.13** shows that liver averages for total animals in this study were within the normal ranges established by Puls (1994), including maximum values. However, minimum values were significantly lower than Puls's recommended concentrations and the scoping review's weighted average. Copper deficiencies in range cattle have been linked to low forage copper content, often caused by copper-deficient soils (Suttle, 1991). Additionally, conditions or diseases impairing copper storage and utilization in ruminants have been documented as contributing factors to deficiencies (Felix et al., 2012). For kidney copper concentrations, all data averages, minimums, and maximums were below the normal ranges for cattle outlined by Puls (1994). Based on Puls's categorizations, these animals would be classified within deficient or marginal ranges. Previous studies on bison tissues similarly report lower copper concentrations in kidney and liver, which have been associated with poor health outcomes (Skibniewska et al., 2006; Rhodes et al., 2018). Muscle copper concentration averages were approximately 1.5 mg/kg D.W. lower than Puls's recommended ranges, with maximum values deviating by about 3 mg/kg dry weight. Conversely, serum copper averages were within Puls's ranges and closely aligned with a singular average from a study included in the scoping review. Plasma copper averages, however, were approximately 0.10 mg/L below the ranges provided by Claypool et al. (1975). The possibly observed copper deficiencies in bison highlight the need for further research to better understand copper metabolism and its role in maintaining health in this species, particularly in relation to diet, environmental factors, and disease impacts.

Table 2.13. Descriptive statistics of copper concentrations within various tissue types across sexes and ages of bison

Copper								
Tissue	Sex	Age	n	Mean	SD	Mode	Min	Max
Liver mg/kg D.W.	Female	<3	248	133.51	68.60	120.97	21.05	310.36
		>3	180	126.83	54.22	119.63	17.39	283.98
		All Ages	428	130.70	62.97	120.44	17.39	310.36
	Male	<3	281	129.09	73.12	112.11	17.21	300.13
		>3	22	134.95	56.84	123.88	48.20	256.80
		All Ages	303	129.51	72.00	112.67	17.21	300.13
	Total			731	130.21	66.82	119.02	17.21
Reference values				30.37*			83.33 - 333.33**	
Kidney mg/kg D.W.	Female	<3	244	6.47	3.56	4.91	2.14	13.41
		>3	168	6.56	3.44	5.46	1.93	13.34
		All Ages	412	6.51	3.51	5.10	1.93	13.41
	Male	<3	284	6.53	3.64	4.89	2.22	16.05
		>3	21	6.81	3.29	5.65	2.93	12.81
		All Ages	305	6.55	3.62	4.92	2.22	16.05
	Total			717	6.52	3.55	4.97	1.93
Reference values				19.46*			20.00 - 30.00**	
Muscle mg/kg D.W.	Female	<3	245	3.09	1.69	2.90	0.42	8.17
		>3	175	3.58	2.12	3.46	0.42	9.53
		All Ages	420	3.29	1.89	3.05	0.42	9.53
	Male	<3	282	3.07	1.70	2.83	0.42	8.26
		>3	22	4.19	2.23	4.50	0.70	8.58
		All Ages	304	3.15	1.77	2.88	0.42	8.58
	Total			724	3.23	1.84	2.99	0.42
Reference values				5.53*			4.80 - 6.00**	
Serum mg/l	Female	<3	247	0.66	0.38	0.57	0.10	1.93
		>3	170	0.69	0.41	0.65	0.12	1.99
		All Ages	417	0.68	0.39	0.59	0.10	1.99
	Male	<3	284	0.69	0.38	0.63	0.11	1.97
		>3	22	0.72	0.36	0.74	0.18	1.34
		All Ages	306	0.69	0.37	0.64	0.11	1.97
	Total			723	0.68	0.38	0.61	0.10
Reference values				†0.70*			0.40 - 1.51**	
Plasma mg/l	Female	<3	247	0.65	0.36	0.61	0.12	1.88
		>3	172	0.66	0.36	0.60	0.10	1.80
		All Ages	419	0.65	0.36	0.61	0.10	1.88
	Male	<3	288	0.66	0.37	0.62	0.10	1.83
		>3	22	0.62	0.35	0.68	0.12	1.31
		All Ages	310	0.66	0.37	0.62	0.10	1.83
	Total			729	0.66	0.36	0.61	0.10
Reference values							0.70 - 1.20***	

¹ Concentrations represented on a dry weight basis (D.W.) where indicated.

² Age in years (<3 years and >3 years). "All ages" indicates all ages of bison within specified sex.

† n=1 article mean from scoping review

* acc. Scoping review weighted means, ** acc. Puls, 1994, ***acc. Claypool et al., 1975

3.4.9. Iron

Table 2.14 presents liver iron concentrations that fall within the ranges reported by Puls (1994). When compared to the scoping review, the weighted mean is substantially higher than the total data average but remains within the range provided by Puls (1994). This discrepancy is likely due to the scoping review's emphasis on wild bison populations, which predominantly consume forage-based diets (Kośła, 1993; Kośła et al., 2013; Klich et al., 2021). Forage consumption is associated with higher dietary iron concentrations, which influence liver iron levels due to the liver's role as the primary site for iron storage and accumulation in ruminants (Broucek, 2014; Chen et al., 2022). By contrast, most animals in this dataset were fed in confinement systems, where iron supplementation is typically required, as observed in the cattle industry (Wagner et al., 2023). Kidney iron concentrations in the dataset are near the lower limit of the range specified by Puls (1994). Similarly, the scoping review's weighted mean falls within Puls's range but is numerically higher than the data averages. The minimum values in the dataset are approximately 90 mg/kg D.W. below the normal range for cattle described by Puls (1994). Muscle iron concentrations in the dataset exceed Puls's averages by approximately 20 mg/kg D.W. Studies comparing the nutrient profiles of bison and cattle meat have consistently demonstrated higher iron concentrations in bison (Marchello et al., 1989; Galbraith et al., 2006). Both minimum and maximum muscle values from the dataset lie outside Puls's ranges, while the scoping review's weighted mean is higher than both the dataset averages and Puls's ranges. Serum and plasma iron concentrations in the dataset are approximately 60 mg/L below the ranges provided by Puls (1994). Additionally, dataset averages are lower than the scoping review's weighted means. While maximum values align with the ranges given by Puls (1994), minimum values are numerically lower than the normal range of beef cattle iron blood content.

Table 2.14. Descriptive statistics of iron concentrations within various tissue types across sexes and ages of bison

Iron								
Tissue	Sex	Age	n	Mean	SD	Mode	Min	Max
Liver mg/kg D.W.	Female	<3	248	175.27	81.99	156.23	40.03	409.61
		>3	180	170.96	83.66	162.35	40.67	611.39
		All Ages	428	173.45	82.63	157.70	40.03	611.39
	Male	<3	281	176.04	90.13	156.28	35.06	484.44
		>3	22	162.48	67.67	162.28	75.45	362.50
		All Ages	303	175.06	88.67	156.28	35.06	484.44
	Total			731	174.12	85.13	156.48	35.06
Reference values				880.87*			150.00 - 1000.00**	
Kidney mg/kg D.W.	Female	<3	246	148.57	41.28	146.74	68.65	237.11
		>3	158	162.35	40.12	165.27	73.25	254.12
		All Ages	404	153.96	41.33	150.52	68.65	254.12
	Male	<3	284	151.43	36.71	151.26	68.65	241.24
		>3	22	162.75	35.15	158.11	106.35	239.83
		All Ages	306	152.25	36.66	151.55	68.65	241.24
	Total			710	153.22	39.37	151.10	68.65
Reference values				783.50*			150.00 - 800.00**	
Muscle mg/kg D.W.	Female	<3	245	88.50	37.23	88.36	26.29	172.16
		>3	175	91.22	36.85	89.69	31.30	170.10
		All Ages	420	89.63	37.05	88.97	26.29	172.16
	Male	<3	282	94.90	37.55	93.56	27.61	172.16
		>3	22	106.41	33.72	112.37	49.48	170.10
		All Ages	304	95.73	37.35	95.24	27.61	172.16
	Total			724	92.19	37.27	90.21	26.29
Reference values				129.37*			30.00 - 70.00**	
Serum mg/l	Female	<3	247	0.96	0.47	0.93	0.25	2.37
		>3	171	1.01	0.51	0.93	0.25	2.35
		All Ages	418	0.98	0.48	0.93	0.25	2.37
	Male	<3	283	0.94	0.46	0.89	0.24	2.55
		>3	22	0.99	0.55	0.91	0.22	2.27
		All Ages	305	0.95	0.46	0.89	0.22	2.55
	Total			723	0.97	0.48	0.92	0.22
Reference values				1.30*			1.60 - 2.50**	
Plasma mg/l	Female	<3	246	0.92	0.50	0.79	0.24	2.63
		>3	171	0.96	0.50	0.83	0.23	2.63
		All Ages	417	0.93	0.50	0.81	0.23	2.63
	Male	<3	286	0.94	0.47	0.87	0.23	2.59
		>3	22	1.00	0.50	0.86	0.33	2.27
		All Ages	308	0.94	0.48	0.87	0.23	2.59
	Total			725	0.94	0.49	0.84	0.23
Reference values							1.30 - 2.50**	

¹ Concentrations represented on a dry weight basis (D.W.) where indicated.

² Age in years (<3 years and >3 years). "All ages" indicates all ages of bison within specified sex.

* acc. Scoping review weighted means, ** acc. Puls, 1994

3.4.10. Potassium

Table 2.15 demonstrates that the total animal average liver potassium concentration falls within the ranges reported by Puls (1994) and aligns closely with the weighted average obtained from the scoping review. However, maximum and minimum values exceed the Puls (1994) ranges by approximately 12,000 mg/kg D.W. on the upper end and 3,000 mg/kg D.W. on the lower end. In contrast, the total animal average kidney potassium concentration remains within the ranges reported by Puls (1994). When comparing the scoping review's weighted mean with the dataset averages, the scoping review's kidney potassium values are more than double the dataset's averages. This discrepancy may reflect potassium conservation mechanisms in the kidney, particularly under conditions of reduced potassium intake. Most bison included in the scoping review were European bison sampled during the winter months (Dębska et al., 2005; Dębska et al., 2006; Kośła et al., 2015; Klich et al., 2021), when forage quality is generally poor. Poor forage quality could contribute to increased potassium concentrations in the kidney, seen in cattle (Ward, 1966; Sanchez et al., 1994). For muscle tissue, the scoping review's weighted average is numerically similar to the dataset's total animal averages. Serum and plasma potassium averages fall within the ranges reported by Puls (1994), although the minimum and maximum values in the dataset extend beyond these ranges. While the scoping review's weighted average for serum and plasma are numerically higher than both the Puls (1994) ranges and dataset averages, overall potassium concentrations do not appear to indicate a significant concern for deficiencies.

Table 2.15. Descriptive statistics of potassium concentrations within various tissue types across sexes and ages of bison

Potassium									
Tissue	Sex	Age	n	Mean	SD	Mode	Min	Max	
Liver mg/kg D.W.	Female	<3	248	7776.91	3744.19	7028.60	1897.35	25333.03	
		>3	180	7717.25	3374.04	7082.51	2222.01	19881.65	
		All Ages	428	7751.82	3589.21	7060.94	1897.35	25333.03	
	Male	<3	281	7642.27	3767.21	7054.36	1878.37	25588.92	
		>3	22	7331.66	3279.11	6684.90	3270.92	14865.43	
		All Ages	303	7619.72	3729.91	7012.62	1878.37	25588.92	
	Total			731	7697.06	3646.24	7048.49	1878.37	25588.92
	Reference values				7918.45*			4666.67 - 13166.67**	
Kidney mg/kg D.W.	Female	<3	244	7481.08	1915.15	8067.05	4859.90	11007.36	
		>3	168	6989.57	1687.60	6228.09	4904.78	10823.69	
		All Ages	412	7280.66	1839.63	6542.07	4859.90	11007.36	
	Male	<3	284	7755.69	1938.91	8514.17	3375.60	13304.46	
		>3	21	6672.47	1455.49	6143.91	5162.93	9831.66	
		All Ages	305	7681.11	1927.31	8424.43	3375.60	13304.46	
	Total			717	7451.00	1886.53	8047.35	3375.60	13304.46
	Reference values				18158.75*			9000.00 - 13000.00**	
Muscle mg/kg D.W.	Female	<3	245	13951.54	2489.11	13752.84	9118.78	19192.78	
		>3	175	14212.57	2420.50	14150.61	9214.70	19473.20	
		All Ages	420	14060.30	2461.22	13931.18	9118.78	19473.20	
	Male	<3	282	13644.82	2508.42	13291.75	9070.37	19577.32	
		>3	22	14657.42	2391.04	14595.88	9446.89	18321.65	
		All Ages	304	13718.10	2510.10	13410.33	9070.37	19577.32	
	Total			724	13916.61	2485.89	13713.49	9070.37	19577.32
	Reference values				12649.09*				
Serum mg/l	Female	<3	248	160.49	62.61	150.21	51.62	349.98	
		>3	170	155.62	65.18	141.19	44.60	358.23	
		All Ages	418	158.51	63.63	147.13	44.60	358.23	
	Male	<3	284	162.31	71.47	148.33	45.34	361.33	
		>3	22	146.20	53.50	134.91	61.69	249.83	
		All Ages	306	161.15	70.38	144.53	45.34	361.33	
	Total			724	159.63	66.53	146.70	44.60	361.33
	Reference values				333.77*			152.50 - 234.60**	
Plasma mg/l	Female	<3	246	165.83	67.68	154.67	45.34	358.23	
		>3	172	167.63	71.18	156.10	56.86	358.23	
		All Ages	418	166.57	69.06	156.10	45.34	358.23	
	Male	<3	288	159.51	62.41	150.56	52.86	336.97	
		>3	22	164.37	73.73	147.51	63.92	329.04	
		All Ages	310	159.85	63.15	150.17	52.86	336.97	
	Total			728	163.71	66.65	152.30	45.34	358.23
	Reference values							152.50 - 234.60**	

¹ Concentrations represented on a dry weight basis (D.W.) where indicated.

² Age in years (<3 years and >3 years). "All ages" indicates all ages of bison within specified sex.

* acc. Scoping review weighted means, ** acc. Puls, 1994

3.4.11. Magnesium

Table 2.16 presents the average liver magnesium concentrations, which are approximately 100 mg/kg D.W. lower than the ranges reported by Puls (1994). In contrast, the weighted average derived from the scoping review falls within the ranges provided by Puls. Although liver magnesium concentrations are not considered reliable indicators of magnesium status, kidney concentrations may offer more insight into magnesium intake in relation to beef cattle (Martens et al., 2018). The overall average kidney magnesium concentrations align with the ranges reported by Puls (1994), with maximum values also within the expected range. Notably, the scoping review's weighted averages for kidney magnesium concentrations are higher than other reported values, potentially reflecting differences in magnesium intake by European bison (Dębska et al., 2006; Kośła et al., 2012). For muscle magnesium concentrations, the difference between the overall averages and the scoping review weighted averages is minimal, at only 1,000 mg/kg D.W. Similarly, the total average serum and plasma magnesium concentrations are numerically close to the weighted averages from the scoping review, both of which fall within the ranges for cattle provided by Puls (1994). Since serum magnesium levels are generally considered reliable indicators of magnesium status (Martens et al., 2018; Becka and Hall, 2023), these findings may suggest that magnesium deficiency is unlikely to be a substantial concern for the animals in question, but still requires further research into the specific mode of action of this mineral in bison.

Table 2.16. Descriptive statistics of magnesium concentrations within various tissue types across sexes and ages of bison

Magnesium									
Tissue	Sex	Age	n	Mean	SD	Mode	Min	Max	
Liver mg/kg D.W.	Female	<3	248	259.20	121.72	234.62	68.74	696.84	
		>3	180	250.18	115.33	227.32	67.64	658.45	
		All Ages	428	255.41	119.02	231.39	67.64	696.84	
	Male	<3	281	261.92	126.16	236.38	69.44	703.88	
		>3	22	256.26	104.67	229.90	118.07	543.95	
		All Ages	303	261.51	124.58	236.38	69.44	703.88	
	Total			731	257.94	121.31	233.24	67.64	703.88
	Reference values				693.91*			333.33 - 833.33**	
Kidney mg/kg D.W.	Female	<3	246	118.71	47.64	114.70	41.15	215.05	
		>3	155	140.90	46.18	146.01	56.17	238.17	
		All Ages	401	127.29	48.25	125.54	41.15	238.17	
	Male	<3	285	111.17	40.61	106.68	39.97	231.31	
		>3	22	149.14	38.44	149.41	83.73	226.37	
		All Ages	307	113.89	41.57	109.14	39.97	231.31	
	Total			708	121.48	45.93	116.86	39.97	238.17
	Reference values				1351.38*			250.00 - 500.00**	
Muscle mg/kg D.W.	Female	<3	245	1140.18	213.58	1134.62	746.50	1632.99	
		>3	175	1174.25	220.53	1157.73	763.99	1640.21	
		All Ages	420	1154.38	216.89	1150.13	746.50	1640.21	
	Male	<3	282	1155.90	240.28	1126.29	741.90	1644.33	
		>3	22	1223.00	229.64	1161.86	903.09	1646.39	
		All Ages	304	1160.75	239.79	1130.28	741.90	1646.39	
	Total			724	1157.05	226.65	1139.42	741.90	1646.39
	Reference values				1030.09*				
Serum mg/l	Female	<3	247	26.00	11.95	23.48	8.58	66.73	
		>3	170	27.90	13.05	25.28	9.36	64.83	
		All Ages	417	26.78	12.43	24.31	8.58	66.73	
	Male	<3	283	26.76	11.94	24.96	8.92	64.83	
		>3	22	26.61	13.91	21.25	12.64	58.34	
		All Ages	305	26.75	12.06	24.88	8.92	64.83	
	Total			722	26.76	12.27	24.39	8.58	66.73
	Reference values				23.67*			18.00 - 35.00**	
Plasma mg/l	Female	<3	247	24.54	10.14	23.11	8.40	58.82	
		>3	172	23.35	8.91	21.50	8.40	50.42	
		All Ages	419	24.05	9.66	22.41	8.40	58.82	
	Male	<3	289	25.11	11.15	22.41	8.07	57.14	
		>3	22	21.74	11.14	17.58	8.07	47.36	
		All Ages	311	24.87	11.16	22.15	8.07	57.14	
	Total			730	24.40	10.32	22.41	8.07	58.82
	Reference values							18.00 - 35.00**	

¹ Concentrations represented on a dry weight basis (D.W.) where indicated.

² Age in years (<3 years and >3 years). "All ages" indicates all ages of bison within specified sex.

* acc. Scoping review weighted means, ** acc. Puls, 1994

3.4.12. *Manganese*

Table 2.17 illustrates that the total average manganese concentration in liver samples is slightly lower than the range reported by Puls (1994). The scoping review average falls within Puls's range but is marginally higher than the total averages. Maximum manganese concentrations exceed the upper range of Puls (1994), except for bison aged over three years, whose values numerically align with Puls's range. Manganese is known to concentrate most in tissues such as bone, liver, kidneys, pituitary gland, and pancreas, and although absorption is low, it is relatively constant (Buchweitz et al., 2023), Kidney data show total averages approximately 1.5 mg/kg dry weight lower than Puls's (1994) ranges. The scoping review's single-article average, however, exceeds all averages and surpasses Puls's (1994) reference ranges. No manganese toxicities in ruminants have been documented to date. However, high dietary levels of calcium, phosphorus, and iron are known to antagonize manganese by reducing its bioavailability (Wagner et al., 2023). In studies investigating bison, Skibniewski et al. (2010) examined manganese concentrations in various tissues of European bison and found higher manganese levels compared to domesticated and free-ranging ruminants in the same area. Muscle manganese averages fall approximately 1.4 mg/kg dry weight below the ranges reported by Puls (1994). However, the weighted average from the scoping review is numerically similar to these reference values. Serum manganese averages and the scoping review mean are consistent with Puls's (1994) range. Plasma data averages also fall within Puls's range, but maximum values are approximately twice as high as the upper limit reported by Puls (1994). Overall, most data averages for Mn are lower than pre-established normal ranges of beef cattle, which could indicate a need for further research to understand any species differences for status of this mineral in the animal.

Table 2.17. Descriptive statistics of manganese concentrations within various tissue types across sexes and ages of bison

Manganese								
Tissue	Sex	Age	n	Mean	SD	Mode	Min	Max
Liver mg/kg D.W.	Female	<3	248	7.95	4.19	7.31	1.40	23.15
		>3	180	7.66	3.33	7.28	1.87	17.86
		All Ages	428	7.83	3.85	7.29	1.40	23.15
	Male	<3	281	8.22	4.52	7.33	1.41	23.38
		>3	22	7.33	2.92	6.83	3.14	13.75
		All Ages	303	8.15	4.42	7.31	1.41	23.38
	Total			731	7.96	4.10	7.29	1.40
Reference values				11.60*			8.33 - 20.00**	
Kidney mg/kg D.W.	Female	<3	246	3.46	1.50	3.55	1.02	7.22
		>3	158	3.59	1.41	3.56	1.02	7.22
		All Ages	404	3.51	1.46	3.55	1.02	7.22
	Male	<3	284	3.80	1.50	3.77	1.09	7.30
		>3	22	3.68	1.37	3.92	1.07	5.71
		All Ages	306	3.80	1.49	3.77	1.07	7.30
	Total			710	3.64	1.48	3.67	1.02
Reference values				†23.00*			5.00 - 10.00**	
Muscle mg/kg D.W.	Female	<3	245	0.59	0.24	0.56	0.17	1.24
		>3	175	0.64	0.25	0.63	0.16	1.40
		All Ages	420	0.61	0.24	0.59	0.16	1.40
	Male	<3	282	0.56	0.21	0.51	0.18	1.23
		>3	22	0.62	0.23	0.59	0.28	1.02
		All Ages	304	0.56	0.21	0.51	0.18	1.23
	Total			724	0.59	0.23	0.55	0.16
Reference values				0.51*			2.00 - 3.80**	
Serum ug/l	Female	<3	247	1.35	0.56	1.24	0.45	2.71
		>3	170	1.33	0.53	1.19	0.41	2.82
		All Ages	417	1.34	0.55	1.23	0.41	2.82
	Male	<3	282	1.34	0.55	1.24	0.41	2.71
		>3	22	1.37	0.54	1.37	0.65	2.60
		All Ages	304	1.34	0.54	1.24	0.41	2.71
	Total			721	1.34	0.54	1.23	0.41
Reference values				†0.60*			0.60 - 7.00**	
Plasma ug/l	Female	<3	246	3.12	2.58	2.22	0.52	15.27
		>3	172	3.19	2.59	2.26	0.59	14.99
		All Ages	418	3.15	2.58	2.23	0.52	15.27
	Male	<3	288	3.04	2.33	2.32	0.45	15.50
		>3	22	4.11	3.38	2.80	0.88	15.50
		All Ages	310	3.12	2.43	2.35	0.45	15.50
	Total			728	3.14	2.52	2.30	0.45
Reference values							0.60 - 7.00**	

¹ Concentrations represented on a dry weight basis (D.W.) where indicated.

² Age in years (<3 years and >3 years). "All ages" indicates all ages of bison within specified sex.

† n=1 article mean from scoping review

* acc. Scoping review weighted means, ** acc. Puls, 1994

3.4.13. Molybdenum

Molybdenum absorption and excretion is highly dependent on sulfur intake for ruminants (NASEM, 2016). Homeostatic control occurs within the kidneys, status is well defined by liver concentrations, and toxicities of molybdenum can interfere with copper uptake as well (Buchweitz et al., 2023). **Table 2.18** shows liver data averages fall within Puls (1994) as do the scoping review weighted average; however, weighted average is numerically 2 mg/kg D.W. higher than data total animal average. Average concentrations of molybdenum in the kidneys are within range of Puls (1994). It is important to note that most maximum values for both kidney and liver concentrations of molybdenum are within toxic ranges specified by Puls (1994) for beef cattle. Due to the low concentrations of molybdenum that are known for many ruminant animals, including cattle and sheep, it could be hypothesized that these animals were experiencing some level of molybdenum toxicity, copper deficiency, or large amount of sulfur intake because of the three-way relationships known for these minerals; However, further research needs to establish correlating health indicators in order to fully analyze the animals condition (Suttle, 1991; Buchweitz et al., 2023). Muscle averages are not within ranges of Puls (1994), and maximum values are 0.06 mg/kg D.W. less than lower end of range from Puls (1994). Serum and plasma data averages are numerically higher than ranges given by Puls (1994) by about 0.04-0.07 mg/l. Therefore, molybdenum values from the study align with pre-established normal ranges of beef cattle for most tissue types.

Table 2.18. Descriptive statistics of molybdenum concentrations within various tissue types across sexes and ages of bison

Molybdenum								
Tissue	Sex	Age	n	Mean	SD	Mode	Min	Max
Liver mg/kg D.W.	Female	<3	248	1.59	0.89	1.42	0.28	5.47
		>3	180	1.60	0.96	1.43	0.26	6.82
		All Ages	428	1.60	0.92	1.43	0.26	6.82
	Male	<3	281	1.58	0.91	1.41	0.23	4.78
		>3	22	1.52	0.81	1.43	0.62	4.55
		All Ages	303	1.58	0.90	1.41	0.23	4.78
	Total			731	1.59	0.91	1.42	0.23
Reference values				3.83*			0.47 - 4.67**	
Kidney mg/kg D.W.	Female	<3	244	2.52	1.06	2.33	0.82	10.47
		>3	168	2.52	0.93	2.43	0.22	7.35
		All Ages	412	2.52	1.01	2.38	0.22	10.47
	Male	<3	284	2.44	0.83	2.37	0.90	6.68
		>3	21	2.51	0.76	2.52	1.34	4.20
		All Ages	305	2.45	0.82	2.37	0.90	6.68
	Total			717	2.49	0.93	2.38	0.22
Reference values							1.10 - 2.85**	
Muscle mg/kg D.W.	Female	<3	245	0.04	0.01	0.04	0.02	0.06
		>3	175	0.04	0.01	0.04	0.02	0.06
		All Ages	420	0.04	0.01	0.04	0.02	0.06
	Male	<3	280	0.04	0.01	0.04	0.02	0.06
		>3	22	0.04	0.01	0.04	0.02	0.06
		All Ages	302	0.04	0.01	0.04	0.02	0.06
	Total			722	0.04	0.01	0.04	0.02
Reference values							0.12 - 1.25**	
Serum mg/l	Female	<3	248	0.14	0.04	0.14	0.07	0.25
		>3	170	0.14	0.04	0.15	0.07	0.24
		All Ages	418	0.14	0.04	0.14	0.07	0.25
	Male	<3	283	0.14	0.04	0.14	0.07	0.24
		>3	22	0.13	0.04	0.15	0.07	0.20
		All Ages	305	0.14	0.04	0.14	0.07	0.24
	Total			723	0.14	0.04	0.14	0.07
Reference values							0.01 - 0.10**	
Plasma mg/l	Female	<3	247	0.17	0.08	0.17	0.04	0.30
		>3	172	0.17	0.07	0.18	0.04	0.30
		All Ages	419	0.17	0.08	0.17	0.04	0.30
	Male	<3	288	0.17	0.08	0.17	0.04	0.30
		>3	22	0.15	0.07	0.15	0.04	0.25
		All Ages	310	0.17	0.07	0.17	0.04	0.30
	Total			729	0.17	0.08	0.17	0.04
Reference values							0.01 - 0.10**	

¹ Concentrations represented on a dry weight basis (D.W.) where indicated.

² Age in years (<3 years and >3 years). "All ages" indicates all ages of bison within specified sex.

* acc. Scoping review weighted means, ** acc. Puls, 1994

3.4.14. Sodium

Table 2.19 shows that average liver concentrations of sodium are lower than ranges given by Puls (1994). Scoping review weighted average does fall within ranges given by Puls and shows a 2500 mg/kg D.W. numerical difference between data average and scoping review weighted mean. Unlike other minerals, the liver has poor suitability for the sodium status of animals, and is best found within muscle and serum samples (Becka and Hall, 2023). Data averages for kidney concentrations of sodium were lower than ranges given by Puls (1994) by about a difference of 1,200 mg/kg D.W. The scoping review weighted average is numerically higher than both data averages and ranges from Puls for sodium concentrations. Muscle concentrations for the scoping review weighted average is about 500 mg/kg D.W. higher concentrated than data averages. The difference between data averages and reference ranges for concentration of sodium in bison muscle could be due to sampling of different muscle groups, since studies comparing different cuts for sodium concentrations did find significant differences (Marchello et al., 1989; Marchello et al., 1998; Galbraith et al., 2006). Serum averages were only marginally lower than ranges set by Puls (1994) by about 200 mg/l. The scoping review weighted average was within Puls (1994) ranges, as well as data average of plasma concentrations of sodium. In all, sodium values from the study align with pre-established normal ranges of beef cattle for most tissue types.

Table 2.19. Descriptive statistics of sodium concentrations within various tissue types across sexes and ages of bison

Sodium								
Tissue	Sex	Age	n	Mean	SD	Mode	Min	Max
Liver mg/kg D.W.	Female	<3	247	2989.06	587.09	3023.47	1681.40	3965.70
		>3	180	2911.88	606.13	2902.08	1664.58	3937.33
		All Ages	427	2956.53	595.71	2959.18	1664.58	3965.70
	Male	<3	278	2951.66	568.15	2935.42	1720.33	3974.12
		>3	21	2757.68	655.30	2758.99	1806.25	3858.16
		All Ages	299	2938.04	575.62	2918.37	1720.33	3974.12
	Total		726	2948.91	587.19	2948.88	1664.58	3974.12
Reference values			5425.50*				3000.00 - 6000.00**	
Kidney mg/kg D.W.	Female	<3	246	5960.53	1062.75	5862.36	4108.44	8458.76
		>3	158	5583.86	893.22	5535.45	4131.12	7880.98
		All Ages	404	5813.22	1015.54	5707.80	4108.44	8458.76
	Male	<3	284	6090.50	983.89	6082.50	4140.36	8558.30
		>3	22	5616.45	1015.75	5700.95	4395.41	7950.19
		All Ages	306	6056.42	992.11	5991.00	4140.36	8558.30
	Total		710	5918.04	1012.01	5814.59	4108.44	8558.30
Reference values			9996.00*				7250.00 - 8500.00**	
Muscle mg/kg D.W.	Female	<3	245	1515.21	302.08	1532.59	925.99	2212.37
		>3	175	1561.44	309.12	1574.23	937.96	2217.53
		All Ages	420	1534.47	305.52	1547.80	925.99	2217.53
	Male	<3	282	1510.32	303.70	1481.64	949.01	2210.31
		>3	22	1564.20	329.56	1532.88	937.04	2119.59
		All Ages	304	1514.22	305.39	1481.87	937.04	2210.31
	Total		724	1525.97	305.42	1521.37	925.99	2217.53
Reference values			2147.40*					
Serum mg/l	Female	<3	248	2939.98	723.41	2793.22	1717.11	5064.88
		>3	170	2851.98	728.80	2627.55	1746.82	4889.90
		All Ages	418	2904.19	726.03	2732.48	1717.11	5064.88
	Male	<3	285	2926.61	751.81	2818.14	1736.04	4885.22
		>3	22	2716.69	681.71	2584.14	1804.04	3980.33
		All Ages	307	2911.57	747.95	2760.26	1736.04	4885.22
	Total		725	2907.32	734.88	2746.09	1717.11	5064.88
Reference values			3166.66*				3105.00 - 3450.00**	
Plasma mg/l	Female	<3	247	3386.55	1012.77	3180.44	377.84	5966.31
		>3	171	3310.08	837.50	3185.44	1555.88	5975.24
		All Ages	418	3355.27	944.70	3181.77	377.84	5975.24
	Male	<3	288	3362.69	918.91	3202.11	2002.54	5909.23
		>3	22	3675.35	926.97	3554.01	2075.44	5696.90
		All Ages	310	3384.88	921.49	3253.55	2002.54	5909.23
	Total		728	3367.88	934.36	3201.02	377.84	5975.24
Reference values							3105.00 - 3450.00**	

¹ Concentrations represented on a dry weight basis (D.W.) where indicated.

² Age in years (<3 years and >3 years). "All ages" indicates all ages of bison within specified sex.

* acc. Scoping review weighted means, ** acc. Puls, 1994

3.4.15. Phosphorus

Phosphorus within the body is mainly distributed into the skeleton and then distributed by the blood (Sharifi et al., 2007). Antagonists include increases of calcium, magnesium, and aluminum, that can result in decreased absorption of phosphorus (Goff, 2000; Sharifi et al., 2007). Typical sources of phosphorus in the diet come from cereal grain, and some plant proteins sources, but is typically low in forages (Goff, 2000; Karn, 2001). **Table 2.20** shows liver total phosphorus values from data falls within ranges of Puls (1994). Kidney data averages are lower than Puls (1994) beef cattle ranges by about 200 mg/kg D.W. except for males over three years, and females under three years. Minimums are ranged, but typically 3,000-4,000 mg/kg D.W. less concentrated than in comparison to Puls (1994) ranges. Scoping review weighted average of muscle concentrations of total phosphorus was closest to data average of young males under the age of three years. Other sex and age averages exhibited around a 500-1000 mg/kg D.W. difference. Studies investigating muscle and phosphorus concentrations within bison have investigated differences of bison and cattle hybrids (Witkowska and Kotik, 1987) and different muscle groups concentrations (Marchello et al., 1998; Galbraith et al., 2006). Collectively, these studies have noted the lower concentrations of total phosphorus in muscle of bison compared to cattle. Serum data average falls within Puls (1994) ranges, as well as is very close to scoping review weighted averages. Plasma average values are close to the lower range values of Puls (1994): only bison over the age of three exhibit to be within the ranges set forth by Puls (1994). Studies investigating blood concentrations of phosphorus have noted differences of age groups and status of total phosphorus as well as larger ranges of concentrations than compared to beef cattle references (Miller et al., 1989; Vestweber et al., 1991).

Table 2.20. Descriptive statistics of total phosphorus concentrations within various tissue types across sexes and ages of bison

Phosphorus (Total)								
Tissue	Sex	Age	n	Mean	SD	Mode	Min	Max
Liver mg/kg D.W.	Female	<3	248	8486.48	1918.15	8643.59	5155.05	12076.58
		>3	179	8271.42	1829.76	8259.21	5335.79	11967.99
		All Ages	427	8396.32	1882.43	8527.25	5155.05	12076.58
	Male	<3	281	8721.26	1960.19	8889.21	4197.97	12198.57
		>3	22	8095.99	1871.41	8185.44	5288.66	11848.31
		All Ages	303	8675.86	1957.65	8807.07	4197.97	12198.57
	Total			730	8512.35	1917.64	8631.51	4197.97
Reference values							666.67 - 13333.33**	
Kidney mg/kg D.W.	Female	<3	244	8105.06	2389.50	8250.00	4468.75	13200.00
		>3	168	7535.77	2061.48	7326.00	4486.84	12759.17
		All Ages	412	7872.93	2276.19	7862.25	4468.75	13200.00
	Male	<3	284	7819.353	2539.072	7679.077	1052.189	13200.00
		>3	21	8206.99	1867.96	8128.42	5002.11	12157.89
		All Ages	305	7846.043	2498.153	7716.049	1052.19	13200.00
	Total			717	7861.49	2371.48	7797.27	1052.19
Reference values							8000.00 - 13000.00**	
Muscle mg/kg D.W.	Female	<3	245	8072.04	1050.41	8042.98	6096.05	10305.15
		>3	175	8413.32	998.34	8342.65	6170.72	10344.33
		All Ages	420	8214.24	1041.54	8169.48	6096.05	10344.33
	Male	<3	281	7972.38	1043.87	7855.15	6053.51	10352.58
		>3	22	8804.17	1362.20	9388.66	6263.32	10232.99
		All Ages	303	8032.78	1089.06	7909.28	6053.51	10352.58
	Total			723	8138.19	1064.75	8091.91	6053.51
Reference values							7756.17*	
Serum mg/l	Female	<3	248	135.09	35.93	132.00	67.64	238.52
		>3	170	140.37	37.81	137.11	73.06	237.36
		All Ages	418	137.24	36.75	133.91	67.64	238.52
	Male	<3	284	138.32	38.12	132.36	70.21	243.04
		>3	22	152.77	40.82	145.91	85.03	235.42
		All Ages	306	139.36	38.43	133.39	70.21	243.04
	Total			724	138.13	37.46	133.77	67.64
Reference values							139.28* 90.00 - 140.00**	
Plasma mg/l	Female	<3	246	87.78	39.48	82.79	20.54	186.54
		>3	171	90.04	41.42	84.26	20.01	195.91
		All Ages	417	88.71	40.25	83.42	20.01	195.91
	Male	<3	289	86.57	40.67	80.05	18.43	193.39
		>3	22	100.40	41.45	101.62	31.60	192.12
		All Ages	311	87.55	40.81	80.58	18.43	193.39
	Total			728	88.21	40.47	82.16	18.43
Reference values							90.00 - 140.00**	

¹ Concentrations represented on a dry weight basis (D.W.) where indicated.

² Age in years (<3 years and >3 years). "All ages" indicates all ages of bison within specified sex.

³ Values calculated from inorganic phosphorus values – assumed 50% inorganic phosphorus

* acc. Scoping review weighted means, ** acc. Puls, 1994

3.4.16. Sulfur

Sulfur is required by microorganisms within a ruminant animal to build sulfur containing amino acids for protein synthesis (Taylor et al., 2013). Sulfur is also important for detoxification reactions and can be converted in areas such as the intestine, liver, and kidney (Felix et al., 2012; Taylor et al., 2013). **Table 2.21** shows liver data averages for sulfur content are within ranges of Taylor et al (2013) as well as are close in relation to the weighted average from the scoping review for bison species. Kidney data averages fall within the range set forth by Taylor et al. (2013). Feed types like dried distiller grains are known to be higher in sulfur concentrations; however, because the majority of animals from the study were consuming whole corn diets with ad libitum forages, the variety of sulfur intake from other products of corn was not a concern for this animals (U.S. Grains Council, 2018). Total average for muscle concentrations of sulfur were lower than averages presented by Honig et al (2022). Serum data averages were lower than ranges from Puls (1994) by about 20 mg/dl as well as plasma averages. Although some water sources of specific areas were found to exhibit high concentrations of sulfates (Table 4), these did not translate over to data observed in bison sampled, so there needs to be more investigation regarding quantities of water consumed by animals, as well as frequency of visits to water sources containing higher amounts of sulfates in order to assess further concern of potential water sources.

Table 2.21. Descriptive statistics of sulfur concentrations within various tissue types across sexes and ages of bison

Sulfur								
Tissue	Sex	Age	n	Mean	SD	Mode	Min	Max
Liver mg/kg D.W.	Female	<3	246	7785.34	1164.45	7850.46	5158.73	10049.47
		>3	180	7787.90	1120.82	7850.00	5112.25	9907.14
		All Ages	426	7786.42	1144.88	7850.46	5112.25	10049.47
	Male	<3	278	7758.91	1118.12	7842.86	5106.12	10101.01
		>3	24	7398.76	1171.88	7054.08	5782.65	9859.82
		All Ages	299	7733.62	1123.72	7805.10	5106.12	10101.01
	Total			725	7764.64	1135.72	7845.92	5106.12
Reference values				10878.45*			3670.00 - 11.041.00***	
Kidney mg/kg D.W.	Female	<3	246	4533.93	1453.16	4708.06	2219.29	6734.28
		>3	158	5289.76	1381.81	5811.34	2859.72	7531.10
		All Ages	404	4829.52	1471.06	5360.46	2219.29	7531.10
	Male	<3	284	4303.97	1164.54	4403.05	1919.34	6600.72
		>3	22	5660.89	1173.30	6050.21	3141.20	6729.73
		All Ages	306	4401.52	1215.07	4487.11	1919.34	6729.73
	Total			710	4645.06	1382.08	4767.46	1919.34
Reference values							4353.00 - 21633.00***	
Muscle mg/kg D.W.	Female	<3	245	2907.46	542.64	2915.04	1868.83	4100.72
		>3	173	2932.23	546.18	2922.80	1863.77	4108.76
		All Ages	418	2917.71	543.59	2915.31	1863.77	4108.76
	Male	<3	281	2906.33	580.59	2889.18	1854.57	4113.61
		>3	22	3004.57	479.21	2830.88	2167.53	3929.38
		All Ages	303	2913.46	573.72	2883.40	1854.57	4113.61
	Total			721	2915.92	556.06	2912.65	1854.57
Reference values				7960.00****				
Serum mg/dl	Female	<3	248	68.86	26.67	61.81	28.91	144.12
		>3	170	69.11	25.86	61.97	30.58	156.32
		All Ages	418	68.96	26.31	61.81	28.91	156.32
	Male	<3	282	69.31	24.93	64.62	30.58	164.45
		>3	22	71.47	24.03	68.59	37.65	130.05
		All Ages	304	69.46	24.84	65.12	30.58	164.45
	Total			722	69.17	25.69	62.66	28.91
Reference values							91.00 - 112.00**	
Plasma mg/dl	Female	<3	247	75.51	35.58	74.28	14.52	160.25
		>3	172	76.04	35.03	77.83	17.01	159.05
		All Ages	419	75.73	35.31	76.52	14.52	160.25
	Male	<3	287	74.46	34.77	75.86	15.64	157.19
		>3	22	68.45	31.72	72.49	15.00	131.36
		All Ages	309	74.03	34.54	75.46	15.00	157.19
	Total			728	75.01	34.97	75.91	14.52
Reference values							96.00 - 108.00**	

¹ Concentrations represented on a dry weight basis (D.W.) where indicated.

² Age in years (<3 years and >3 years). "All ages" indicates all ages of bison within specified sex.

* acc. Scoping review weighted means, ** acc. Puls, 1994, *** acc. Taylor et al., 2013,

**** acc. Honig et al., 2022

3.4.17. Selenium

Selenium is required for growth and immune support for beef cattle, and is also known for the formation of glutathione peroxidase (GSH-PX) which aids in regulation of hydrogen peroxide levels in tissues (Buchweitz et al., 2023; Wagner et al., 2023). Toxicity of selenium is very low in confinement beef cattle, but can be found regionally for grazing ungulates. (Medeiros et al., 1993; Wagner et al., 2023). **Table 2.22** shows liver total average fits within Puls (1994) beef cattle range, but males of all ages fell short of falling within ranges, while females did hit the ranges. Kidney data averages, minimums, modes, and maximums did not fall into the range given by Puls (1994); however, one article through scoping review was within Puls range for bison. Muscle data averages fell within ranges from Puls (1994), but was about 40 mg/kg D.W. lower than weighted mean calculated from scoping review. The range in selenium content between bison sampled for this study and a majority of the bison populations within the scoping review is the locations that they were sampled. Selenium toxicity is a high concern for bison populations within Poland, due to the higher percent of seleniferous accumulator plants within the polish wilderness, as well as other wilderness locations across the globe (Sikarskie et al., 1989; Deore et al., 2002; Kośła et al., 2019). Serum averages were lower than Puls (1994) ranges by about 20 ug/l, but fell closer to scoping review weighted mean. Plasma averages fell within ranges by Puls (1994). Although selenium toxicities may not be a major problem for feedlot raised bison within today's industry, selenium supplementation may need to be further investigated in confinement bison for proper bone growth as well as supporting immune functions.

Table 2.22. Descriptive statistics of selenium concentrations within various tissue types across sexes and ages of bison

Selenium								
Tissue	Sex	Age	n	Mean	SD	Mode	Min	Max
Liver mg/kg D.W.	Female	<3	247	0.87	0.42	0.93	0.11	1.59
		>3	180	0.85	0.44	0.84	0.11	1.59
		All Ages	427	0.86	0.43	0.85	0.11	1.59
	Male	<3	278	0.82	0.43	0.84	0.11	1.59
		>3	21	0.76	0.44	0.83	0.11	1.61
		All Ages	299	0.81	0.43	0.83	0.11	1.61
	Total			726	0.84	0.43	0.84	0.11
Reference values				1.03*			0.83 - 1.67**	
Kidney mg/kg D.W.	Female	<3	246	2.19	0.93	2.21	0.60	4.19
		>3	158	2.31	0.95	2.41	0.61	4.08
		All Ages	404	2.24	0.93	2.30	0.60	4.19
	Male	<3	284	2.32	0.93	2.40	0.54	4.17
		>3	22	2.56	0.93	2.78	0.71	3.94
		All Ages	306	2.34	0.93	2.45	0.54	4.17
	Total			710	2.28	0.93	2.38	0.54
Reference values				†5.02*			5.00 - 7.50**	
Muscle mg/kg D.W.	Female	<3	245	0.49	0.15	0.51	0.09	0.85
		>3	175	0.49	0.14	0.49	0.11	0.79
		All Ages	420	0.49	0.14	0.50	0.09	0.85
	Male	<3	282	0.47	0.15	0.48	0.08	0.87
		>3	22	0.48	0.13	0.47	0.20	0.77
		All Ages	304	0.47	0.14	0.48	0.08	0.87
	Total			724	0.48	0.14	0.49	0.08
Reference values				0.94*			0.28 - 0.60**	
Serum ug/l	Female	<3	246	62.90	30.19	58.38	17.80	168.18
		>3	169	59.31	29.34	54.26	10.77	154.10
		All Ages	415	61.44	29.86	56.62	10.77	168.18
	Male	<3	283	59.87	32.25	52.72	9.94	152.52
		>3	22	56.74	29.04	51.33	18.76	128.96
		All Ages	305	59.65	32.00	52.72	9.94	152.52
	Total			720	60.68	30.78	54.93	9.94
Reference values				58.88*			80.00 - 300.00**	
Plasma ug/l	Female	<3	246	110.09	80.06	84.49	20.00	461.45
		>3	171	112.29	74.51	95.22	20.69	369.16
		All Ages	417	111.00	77.75	86.38	20.00	461.45
	Male	<3	288	114.16	93.65	80.96	1.78	484.52
		>3	22	146.76	118.93	112.43	28.57	503.90
		All Ages	310	116.47	95.80	84.59	1.78	503.90
	Total			727	113.33	85.89	85.70	1.78
Reference values							80.00 - 300.00**	

¹ Concentrations represented on a dry weight basis (D.W.) where indicated.

² Age in years (<3 years and >3 years). "All ages" indicates all ages of bison within specified sex.

† n=1 mean from scoping review

* acc. Scoping review weighted means, ** acc. Puls, 1994

3.4.18. Zinc

Table 2.23 shows liver zinc data averages were within ranges from Puls (1994). The scoping review weighted mean was found to be numerically higher by about 200 mg/kg D.W. and is outside the higher value of Puls (1994) range. Zinc liver concentrations are suitable for determining status in beef cattle, and concentrations of zinc are important for reproductive processes and immunity (Buchweitz et al., 2023; Wagner et al., 2023). Kidney's total average of zinc was lower than lower values of Puls (1994) range by about 10 mg/kg dry weight. Kidney values of zinc are not well known for determining concentrations for the zinc status of an animal since zinc excretion usually occurs as endogenous losses, saliva, and through protein secretion (Wagner et al., 2023). Studies using bison to investigate zinc concentrations within various tissues utilized European bison in comparison to domestic cattle species (Kośła, 1993; Kośła et al., 2004; Durkalec et al., 2018; Klich et al., 2023). A study by Kośła et al (2004) concluded differences of zinc concentrations in different ages of bison in the kidney, and that concentrations of zinc were almost four times more concentrated than previously studied cattle within the same region. Conversely, a study by MacNeil et al. (1990) analyzed American bison and found no differences within liver and kidney concentrations between bison and domestic cattle reference ranges. Muscle data averages were within Puls (1994) ranges, and the scoping review weighted mean was higher than data average. In all, these three tissues analyzed were close to known beef cattle ranges from Puls (1994). Scoping review means were greater due to animals sampled being from the Polish regions, were zinc accumulation in plants in higher and dependent on the acidity of the soil (Kośła et al., 2004). The only values that are all marginally similar are the plasma and serum results, with both the scoping review mean and data averages being within ranges of Puls (1994).

Table 2.23. Descriptive statistics of zinc concentrations within various tissue types across sexes and ages of bison

Zinc								
Tissue	Sex	Age	n	Mean	SD	Mode	Min	Max
Liver mg/kg D.W.		<3	247	200.03	81.53	206.14	56.12	359.72
	Female	>3	180	195.18	78.99	205.19	62.24	353.54
		All Ages	427	197.99	80.41	205.21	56.12	359.72
		<3	278	193.18	77.84	197.89	56.69	356.12
	Male	>3	21	213.30	77.87	203.13	70.41	318.49
		All Ages	299	194.59	77.88	197.96	56.69	356.12
		Total	726	196.59	79.34	203.07	56.12	359.72
		Reference values			382.94*			83.33 - 333.33**
Kidney mg/kg D.W.		<3	246	78.96	20.32	77.89	33.95	131.50
	Female	>3	158	78.57	18.49	76.84	42.52	134.26
		All Ages	404	78.81	19.60	77.58	33.95	134.26
		<3	284	80.90	21.08	79.22	32.46	138.42
	Male	>3	22	74.51	16.32	75.35	54.29	107.48
		All Ages	306	80.44	20.82	78.74	32.46	138.42
		Total	710	79.51	20.14	77.89	32.46	138.42
		Okoren, 2025			423.78			90.00 - 125.00**
Muscle mg/kg D.W.		<3	245	85.90	16.97	84.72	43.50	137.46
	Female	>3	175	87.04	17.80	84.73	49.14	140.12
		All Ages	420	86.38	17.31	84.72	43.50	140.12
		<3	282	88.20	18.96	88.34	42.25	139.69
	Male	>3	22	81.77	18.65	84.64	42.58	128.21
		All Ages	304	87.74	18.98	87.86	42.25	139.69
		Total	724	86.95	18.03	86.17	42.25	140.12
		Reference values			154.23*			80.00 - 120.00**
Serum mg/l		<3	248	1.09	0.62	0.96	0.17	3.75
	Female	>3	170	1.09	0.63	0.98	0.20	3.41
		All Ages	418	1.09	0.62	0.96	0.17	3.75
		<3	282	1.16	0.62	1.04	0.17	2.83
	Male	>3	22	1.11	0.74	0.86	0.20	2.78
		All Ages	304	1.16	0.63	1.04	0.17	2.83
		Total	722	1.12	0.63	0.99	0.17	3.75
		Reference values			†0.90*			0.80 - 1.40**
Plasma mg/l		<3	247	1.17	0.83	0.98	0.11	5.29
	Female	>3	171	1.09	0.69	0.95	0.08	3.61
		All Ages	418	1.14	0.78	0.97	0.08	5.29
		<3	287	1.09	0.75	0.89	0.10	4.52
	Male	>3	22	1.14	0.78	1.07	0.14	3.11
		All Ages	309	1.09	0.75	0.89	0.10	4.52
		Total	727	1.12	0.77	0.94	0.08	5.29
		Reference values						0.80 - 1.40**

¹ Concentrations represented on a dry weight basis (D.W.) where indicated.

² Age in years (<3 years and >3 years). "All ages" indicates all ages of bison within specified sex.

† n=1 mean from scoping review

* acc. Scoping review weighted means, ** acc. Puls, 1994

4. Conclusions

Although most mineral and vitamin concentrations are within pre-established normal ranges set forth by beef cattle research, there are certain nutrients, such as copper, magnesium, and manganese, that lend themselves for future research within metabolism and storage in bison. To address the knowledge gap in vitamin and mineral status of farmed bison, we established baseline data to support future research in bison nutrition. This foundational information will aid in further exploration to improving management practices, optimizing dietary formulations, and enhancing overall herd health & productivity of farmed American bison.

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APPENDIX - IN VITRO RUMEN DIGESTIBILITY OF RANGELAND AND CONCENTRATE DIETS FROM FARMED AMERICAN BISON³

1. Introduction

The American bison (*Bison bison*) has seen a recovery in popularity as a species, as well as in ranching and meat production in the United States and Canada (National Bison Association, 2024). Despite this growth, much of the nutritional understanding of bison is generalized from cattle, which may overlook critical species-specific differences (Lulka, 2006; National Bison Association, 2024). Bison exhibit unique digestive efficiencies compared to cattle, particularly in their ability to process high-fiber forages such as sedges and grasses. This advantage stems from longer feed retention times in the digestive tract, allowing greater breakdown of fibrous material (Schaefer et al., 1978; Hawley et al., 1981; Hawley, 2021; Hecker et al., 2021b). Furthermore, bison face distinct challenges, such as seasonal stressors and sex-based nutritional variations, which influence their dietary needs and efficiency (Schaefer et al., 1978; Hawley et al., 1981; Berini and Badgley, 2017). These differences are particularly pronounced in feedlot settings, where bison tend to have lower dry matter intake and slower weight gain compared to cattle, highlighting the need for tailored feeding strategies (Lulka, 2006; Craine, 2021).

Rumen fermentation, a critical process that determines feed breakdown and nutrient availability, is often studied using cattle as a model species. This process produces volatile fatty acids (VFAs) acetic, propionic, and butyric acids—which are essential for energy production, rumen development and function, and fat storage. Studies on cattle have shown that VFAs typically account for 55–70% of total fermentation products for acetic acid, 15–30% for propionic acid, and 5–15% for butyric acid (Wolin, 1960; Wang et al., 2019; Ellis et al., 2020). However, limited research has focused on bison, raising questions about how their rumen

fermentation characteristics differ and how specific diets may affect these processes. Current findings suggest bison outperform cattle in digesting forages, potentially due to better adaptation to high-fiber diets (Hawley et al., 1981; Hecker et al., 2021a, 2021b). Additionally, exploring the use of tailored inoculum may further optimize fermentation efficiency and forage digestibility for bison (Hawley, 1981; Hawley, 2021). More research is crucial to refine feeding management and improve our understanding of rumen fermentation in this species, particularly under intensive management systems designed to maximize production efficiency. The objective of this study is to examine the impact of diet type on in vitro rumen fermentation characteristics using rumen fluid collected from grain-fed and grass-fed American Bison (*Bison bison*) by assessing multiple VFA concentrations and dry matter disappearances through in vitro to improve our estimates into rumen fermentation characteristics of bison.

2. Materials and Methods

Rumen fluid was collected from six farmed American bison at a commercial slaughter facility. Due to the availability of processing, two collection days were utilized to obtain and begin analysis of samples. Collection day 1 was in June 2023 for grain-fed bison (n = 3 heifers of <3 years of age), while collection day 2 was in November 2023 for grass-fed bison (n = 3 cows of >3 years of age). On both collection days, approximately 400 mL of rumen fluid was collected from each animal's rumen postmortem. Fluid was filtered once through 4 layers of cheesecloth and collected into individual pre-warmed 39°C (102.2° F) thermoses. Filtered rumen fluid was then combined into a 2.0 L beaker with 600.0 mL of 39°C (102.2° F) McDougall's buffer solution at a 1:1 ratio, simulating saliva production during rumination (Tilley and Terry, 1963).

In order to assess rumen fermentation characteristics and calculate digestibility coefficients of minerals and vitamins from high concentrate and forage based diets,

approximately 2.0 kg (wet weight) of a typical concentrate diet and a typical roughage diet fed to bison sampled was collected, dried in a forced air-drying oven at 60°C for 72 hours and ground through a 2.0 mm screen using a Wiley mill (Thomas Scientific, Swedesboro, NJ). The ground ration was weighed to 0.5 grams (± 0.005 g) and dispensed into 25 pre-labeled 50.0 mL conical tubes.

Thirty mL of McDougall's buffer/rumen fluid mixture was added to each pre-weighed 50.0 mL conical tubes containing no substrate (blanks) or 0.5 g of ground substrate (5 sets of 5 blank and 5 diet-specific feed tubes). Tubes were capped with one-way valves and incubated at 72°C for interval times of 0, 12, 24, 48, and 72 hours. To simulate rumen motility, all tubes were gently swirled continuously throughout the incubation process. At the end of the incubation periods, sets of tubes were centrifuged at 2000 x g for 20 minutes. A 2.0 ml aliquot of the supernatant was acidified with 25% (vol/vol) meta-phosphoric acid, and frozen at -80°C until analyzed for volatile fatty acid concentrations via gas chromatography. The remainder of the tubes were dried in a 15°C oven for 24 hours to obtain dry matter disappearance (DMD).

2.1. Statistical Analysis

Utilizing R 4.2.2 (R Core Team, 2021), in vitro DMD of the substrate comparisons of linear, quadratic, and cubic models were completed using Akaike Information Criterion (AIC). The linear model emerged as the optimal choice with the lowest AIC score and a Δ AIC of 2.35 compared to the quadratic model for grass-fed bison rumen fluid. For grain-fed bison, the AIC was utilized to exhibit the quadratic model as the optimal choice with a Δ AIC of 1.34 compared to the cubic model for grain-fed bison rumen fluid. Utilizing AIC, the cubic model emerged as the optimal choice for each VFA proportion and its correlated diet type. The Δ AIC of the cubic model to the quadratic model for acetic, propionic, isobutyric, and butyric acid were 3.96, 1.39,

3.94, and 6.75 for grass-fed bison and 18.69, 24.16, 6.03, and 17.50 for grain-fed bison.

Descriptive statistics were used to describe the fermentation characteristics for rumen fluid collected from bison from each diet type.

3. Results and Discussion

DMD in rumen fermentation is a measure of feed degradability which can show nutrient breakdown and microbe digestion efficiency, and can be affected by many factors, including feed type, particle size, and preexisting microbial populations (Tagawa et al., 2016; Phesatcha et al., 2020) The final 72h DMD percentage was $84.45\% \pm 0.05$ and $69.94\% \pm 0.11$ for grain-fed and grass-fed bison, respectively (**Table A1**). Grain diets are assumed to show increased DMD over initial periods of incubation time, but by 72 hours, grass-diets are likely to exhibit similar dry matter disappearance (Mjoun et al., 2018). Especially when examining bison, these animals have been shown to have greater forage digestion qualities than that compared to domestic cattle (Hawley et al., 1981; Mjoun et al., 2018). When fitting contrasts utilizing AIC, grain-fed bison fit better to a quadratic response ($p < 0.5$) while grass-fed exhibited a linear response ($p < 0.05$). Previous literature expects DMD to exhibit a linear response over time due to the in vitro limitations to microbes utilizing feedstuff for the conversion into VFAs (Ellis et al., 2020, Moloney et al., 1996, Wolin, 1960).

Molar proportions for 72h of acetic, propionic, isobutyric, and butyric acid were $55.26\% \pm 0.01$, $25.80\% \pm 0.002$, $1.93\% \pm 0.00$, and $17.02\% \pm 0.001$ for grain-fed bison and $30.98\% \pm 0.02$, $41.19\% \pm 0.02$, $3.90\% \pm 0.01$, and $23.21\% \pm 0.01$ for grass-fed bison (**Table A2**). Grain-fed bison results for molar proportions agrees with previous literature; however, grass-fed results deviated from previous literature by higher propionate proportions and concentrations (**Figure A1**) than acetate (Wolin, 1960; Hawley et al., 1981; Wang et al., 2019). Due to different

collection days and use of two different sex classes of bison, deviations between both results needs to be taken into consideration. The selection of similar bison with a controlled diet as well as same day of collection could help reduce variability for future results. The other factors that need to be addressed are coordination of keeping accurate temperatures of fluid while collection and processing occurred. Rumen fluid was collected within a commercial slaughter facility, but all processing was done in an external environment, prone to temperatures and other constraints. The refining of procedures and controlling the environment and laboratory space could also help future results.

Table A1. In vitro DMD over time of incubation

Time	Diet¹	Mean²	SD
0	Grain	30.00%	0.02
12	Grain	43.77%	0.09
24	Grain	53.08%	0.05
48	Grain	68.30%	0.11
72	Grain	84.45%	0.13
0	Grass	30.99%	0.04
12	Grass	33.75%	0.01
24	Grass	46.24%	0.03
48	Grass	50.74%	0.07
72	Grass	69.94%	0.25

¹DMD for diet type is confounded by time of collection

² %DMD exhibited a quadratic response ($P < 0.05$) for grain-fed and a linear response ($P < 0.05$) for grass-fed over time

Table A2. In vitro VFA molar proportions over differing diet types at 72h incubation

VFA	Grain-fed Diet ¹		Grass-fed Diet ¹	
	Mean ²	SD	Mean ²	SD
Acetate	55.30%	0.01	31.00%	0.02
Propionate	25.80%	0.002	41.20%	0.02
Butyrate	17.00%	0.001	23.20%	0.01
Isobutyrate	1.90%	0.01	3.90%	0.01

¹VFA molar proportions for diet type is confounded by time of collection

²Molar proportions (mm/100mmMol) of VFA exhibited a cubic response ($P < 0.05$) over time for grain-fed and grass-fed bison

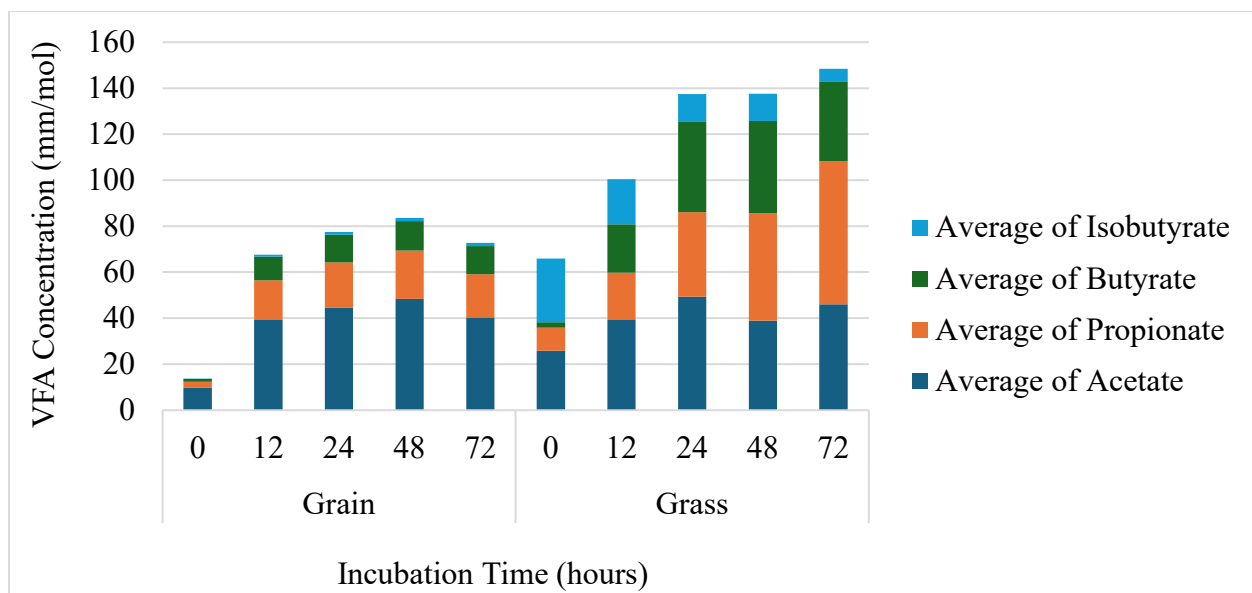


Figure A1. Total in vitro VFA concentrations of differing diet types over time of incubation

4. Summary

This preliminary study explored the use of in vitro rumen fermentation with bison rumen fluid to enhance understanding of bison-specific fermentation characteristics. Limited research exists on the effects of differing feeding systems, such as grass-fed versus grain-fed diets, on digestibility and volatile fatty acid (VFA) concentrations in bison. However, previous studies have demonstrated that bison exhibit greater digestibility of low-quality forages compared to cattle, highlighting their unique adaptation to high-fiber diets (Hawley et al., 1978; Hecker et al., 2021b; Schaefer et al., 1978) These findings could provide valuable insights into the nutritional

requirements of bison and their capacity to perform under various management systems. By investigating how diet influences fermentation characteristics and nutrient breakdown, this study contributes to the foundational knowledge necessary to optimize feeding strategies and improve the efficiency of bison production. Further research is critical to build on these findings and refine dietary approaches tailored to the specific digestive physiology of bison.

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