CARBON STOCK AND PLANT COMMUNITIES ACROSS AN ELEVATION GRADIENT OF A SEMIARID GRASSLAND: A 58-YEAR FOLLOW UP

by

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Carbon Stock and Plant Communities across an Elevation Gradient of a Semiarid Grassland: A 58-Year Follow up

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Abstract

Soil and plant communities were examined across an elevation gradient of a grassland steppe ecosystem in the Southern Interior of British Columbia over 58 years (i.e., from1961 to 2019). In 1961, three distinct zones were classified according to plant species composition and Chernozemic great groups. At the time, grasslands in the area had been in degraded states due to long-term overgrazing, but improved grazing management was put in place in mid-1970s. The objective of my study was to determine topographic, microclimate and soil variables that affect the distribution of Chernozemic great groups and associated soil carbon (C) (i.e., total, organic, active C) and plant communities over an elevation gradient at the Lac du Bois Grassland while reassessing the boundaries of three Chernozemic great groups as established in 1961 by the study of van Ryswyk et al. (1966). While soil C stock and plant composition at the lower grassland remained similar to 1961, the middle and upper grasslands have undergone notable changes. Both have progressed from early seral stage to late seral stage communities, showing recovery from the degraded state in 1961. The middle grassland, which used to be a unique grassland zone, has become a more mesic continuation of the lower grassland's plant species composition with increased biomass and decreased bare soil. Similarly, soil C content only marginally increased from the lower to middle grasslands. Interestingly, during the 58-year period, soil C stock has not increased and may have even decreased in the middle and upper grassland despite the improved plant species composition. Soil organic C at the 0-15 cm depth showed a 7-fold increase (0.9% to 6.8%) from the lowest to highest elevation, while there was a 3-fold increase in C stock (2.87 to 8.51 kg m^{-2}), indicating that elevation remains the primary factor that affects soil C distribution across this landscape due to its effect on effective precipitation and air temperature.

Lay Summary

As atmospheric CO_2 reaches all-time highs, understanding how soil carbon stocks change over time is crucial. An estimated 30% of the global terrestrial carbon pool is found in grassland soils, making them of particular interest for carbon storage research. In 1961, the Lac du Bois Grassland in the Southern Interior of British Columbia was differentiated into three grassland zones based on vegetation and soil type due to an increase in elevation from 350 to 950 metres. This corresponded to a 6-fold increase in soil organic carbon (1.3 to 8.1%C) and a decreasing annual water deficit with elevation. I re-sampled the same study locations and found out that there has been notable grassland plant recovery over 58 years, but unchanged or even decreased soil carbon stocks across the grassland.

Preface

This thesis represents unpublished work which I conducted with assistance from undergraduate students and advisors. I was the lead investigator in the studies included in Chapter 2 and was responsible for major areas of research question formation, data collection, data analysis and thesis composition. Weather stations were established in 2017 by Dr. Brian Wallace. Sample collection assistance was provided by Dr. Brian Wallace, Dr. Maja Krzic, Dr. Reg Newman, Aaron Penner, Seanna Zintel and Adam Pistawka. Justin Kim and Xin Yang provided laboratory assistance. Dr. Maja Krzic and Dr. Brian Wallace were the supervisory authors on this project and were actively involved in all aspects of the thesis. Dr. Gary Bradfield also contributed project guidance and advice on data analysis and presentation.

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List of Abbreviations

a.s.l. - Above Sea Level

BC - British Columbia

BEC - Biogeoclimatic Ecosystem Classification

BGxh2 - Thompson Very Dry Hot Bunchgrass Variant

BGxw1 - Very Dry Warm Bunchgrass Variant

C - Carbon

CEC - Cation Exchange Capacity

CFC - Coarse Fragment Content

DAEP - Dilute Acid Extractable Polysaccharides

DEM - Digital Elevation Model

IDFxh2 - Very Dry Hot Interior Douglas-fir

LG - Lower Grassland

MAP - Mean Annual Precipitation

MAT - Mean Annual Temperature

MG - Middle Grassland

P/E - Precipitation Effectiveness

PNB - Pacific Northwest Bunchgrass

POXC - Permanganate-oxidizable carbon

SIC - Soil Inorganic Carbon

SOC - Soil Organic Carbon

UG - Upper Grassland

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Chapter 1: General Introduction

1.1 Grasslands of British Columbia

Grassland ecosystems cover more than 40% of the global terrestrial area (Suttie, 2005; Hewins et al., 2018) and offer numerous ecosystem benefits and services such as wildlife habitat, livestock forage, and soil carbon (C) storage, which is estimated to represent 20- 30% of the terrestrial C pool (Follett, 2000; Abdalla et al. 2018). Grassland soils are a critical C sink of the global C cycle that are characterized by an ongoing addition and stabilization of organic matter that typically outweighs the slow decomposition due to limited soil water. Historical and present grazing management strategies can significantly alter above and belowground C processes as a result of an alteration to plant species composition (McSheary and Ritchie, 2013) with varied effects on soil C stocks that differ by climate and soil texture (Conant et al., 2017; Thomas et al., 2017). A better understanding of plant community assemblages and associated soil C stocks at a regional level will greatly improve our ability to maintain and increase all the ecosystem benefits and services that grasslands provide (Hewins et al., 2018).

Canada, with 3.17 million km^2 of grassland ecosystems, is ranked fourth among the countries with the largest grassland areas (Suttie, 2005), but only a small portion of the Canadian grasslands are found in British Columbia (BC) with majority of them in the Prairie provinces. In BC, grassland ecosystems are located mainly in the Central and Southern Interior, Cariboo Chilcotin, Rocky Mountain trench and Peace River region, bordered by the Rocky Mountains to the east and Coast Mountains to the west (BC Parks, 2000). It is estimated that grasslands cover around 1% of the total area of the province (Wikeem et al., 1993).

The grasslands of BC are unique in terms of their vegetation, evolutionary development, topography and current use. These grasslands are bunchgrass dominated, unlike the mixed grass prairies of the Northern Great Plains (Shorthouse, 2010). After the last glaciation event ended about 10,000 years ago, most vegetation in Canada was cleared from the land (Daubenmire, 1970). Recolonization of vegetation in BC grasslands occurred from the plants of the bunchgrass steppe ecosystem of the Palouse prairie or Pacific Northwest Bunchgrass (PNB) prairie (Weaver, 1924; Weaver and Clements, 1938; Tisdale, 1947; Endress et al., 2020). The Palouse prairie or PNB is a region that extends from central Oregon, across Washington, Idaho, parts of western Montana and into BC (Daubenmire, 1970).

BC grasslands and the Canadian Prairies also have had different evolutionary drivers (Mack and Thompson, 1982). Bison played a large role in the development of the interior plains of Canada, grazing in very dense, large mobs. This was not the case in BC or the Palouse prairie, where less intense grazing by wild ungulate was dominant (Mack and Thompson, 1982).

BC grasslands and the Canadian Prairies also have different precipitation regimes, which further altered their evolutionary history and current condition (Laurenroth et al., 2014). BC grasslands will receive much of its moisture in the spring from snow melt, and almost no rainfall over the summer months, leading to cool season C_3 plants dominating the vegetation in these areas (Tisdale, 1947). In the Northern Great Plains, there is a mix of cool season C_3 plants growing early in the season, with C_4 grasses dominating in the prime growing summer months, as there is still enough of the soil water to maintain their growth (Barnes and Harrison, 1982; Barnes et al., 1983). Grasslands in the Interior of BC are in the rain shadow of the Coast Mountains, receiving an average of 278 mm of annual precipitation (Environment Canada, 2020), while the Canadian Prairies receive an average 454 mm annual precipitation (McGinn, 2010). Most of BC grasslands are associated with an undulating topography with significant elevation changes over short distances. This leads to a diverse microclimate, plant communities and soil types over relatively small distances across the landscape.

The Northern Great Plains of Canada have been widely converted to agricultural use, due to their even topography and fertile soil, leaving very few native grasslands (Pennock, 2011; PCAP Partnership, 2003). Similarly, grasslands in BC and all of the PNB prairie have been greatly modified and have become very threatened (Samson and Knopf, 1994; Noss et al., 1995; Endress et al., 2020). This is furthered by the fact that many grasslands in BC were and are still used for livestock grazing (BC Parks, 2000) leaving legacies of disturbance from periods of overgrazing (Tisdale and McLean, 1957; van Ryswyk et al., 1966; Watson, 1977; Holechek, 1981; Campbell and Bawtree, 1998).

Even though grasslands cover just 1% of BC, they are very important ecosystems in the province. Grassland soils are known to store large amounts of C (Follett, 2000), but little is known about the depth and distribution of soil C in grassland ecosystems of BC. They are also a very important aspect of the province's ecosystem diversity, with 200 threatened or endangered flora and faunal species, as well as almost 30% of BC's biodiversity hotspots (Gayton, 2003). Due to their beauty, easily traversable topography, open views and unique wildlife, grasslands are regularly used for recreation. It has been estimated that 99% of the original 8 million hectares of bunchgrass grassland in the Palouse Prairie has undergone massive land-use change and other alterations (Hanson et al., 2008; Dixon et al., 2014). Grasslands of BC also play a key role in supporting cattle ranching industry by providing spring to winter grazing, reducing the need for animal feeding operations. Despite providing numerous ecosystem services, grasslands in BC are threatened by urbanization, agricultural conversion, over-grazing, fragmentation and the introduction and spread of non-native species (Carlyle et al., 2014), emphasizing the need for their better protection.

1.2 Soil Carbon Sequestration in Grassland Ecosystems

The dominant soil forming process in grassland soils, or Chernozems, is the accumulation of organic matter in the so-called Chernozemic Ah horizon (Soil Classification Working Group, 1998; Pennock et al., 2011). The features of this horizon include the following: (i) its colour value darker than 5.5 dry or 3.5 moist and has a chroma of less than 3.5 moist, (ii) it is at least 10 cm thick, (iii) it has a color value at least one Munsell unit darker than that of the IC horizon, (iv) it contains 1-17% organic C and its C:N ratio is less than 17, (v) characteristically has neither massive structure and hard consistence nor single-grained structure, when dry, (vi) base saturation greater than 80% and calcium is dominant exchangeable cation, (vii) restricted to soils having a mean annual temperature of 0°C or higher and a soil moisture regime subclass drier than humid (Soil Classification Working Group, 1998). Organic matter accumulation in the Chernozemic Ah horizon is a result of interactions between plant and animal inputs, biochemical properties of inputs, microbial activity, climate, micro, meso and macrofaunal activity, and chemical and physical protection of organic matter within aggregates. The constant addition and stabilization of organic matter typically outweighs the slow decomposition which occurs in these semiarid grasslands due to low soil water, resulting in organic matter accumulation.

Similar to other grassland areas in North America (e.g., Derner, 2007; De Deyn, 2008), grasslands in BC have a pronounced annual water deficit causing bunchgrass species to dominate the vegetation and develop large root networks to access often limited soil water (Carder, 1970). Bunchgrasses grow from a single tuft outward to shade the ground and collect as much rainfall as possible to channel into its central root system (Sinclair, 2006). Grass and forb species, including bunchgrass, devote large proportions (>50%) of the C they assimilate to belowground biomass and root exudates. Of the C that gets translocated belowground, 50% ends up in the roots, while 30% is added to the soil as root exudates and the remaining portion is given off as CO_2 (Kuzyakov and Domanski, 2000). Relative to the aboveground biomass, belowground biomass has a much higher chance of being added to the soil C stock because it is primed for physical and chemical protection against decomposition (Rasse, 2005). Exposure to ultraviolent radiation from the sun, especially in more arid grasslands, can photodegrade about 30% of plant litter that results in a release of CO_2 back into the atmosphere (Lin and King, 2014; Predick, 2018). The aboveground biomass that is not photodegraded can end up in the soil, but that depends on faunal shredding and mixing, vegetation trampling, grazing and subsequent dung deposition. Pennock et al. (2011) suggested that the accumulation of organic matter and thickness of the Ah are not only reliant on the mixing action done by earthworms, but also involves action of other larger soil fauna such as moles, voles, and ground squirrels.

Soil organic matter (SOM) stabilization refers to the obstruction of the decomposition process leading to organic matter accumulation. SOM stabilization in Chernozemic soils is due to a number of factors. For example, finer textured soils can hold more soil organic C (SOC) than a sandy soil. Historically, percent clay has been thought to have the strongest correlation to SOC (Burke et al., 1989; Buschiazzo et al., 1991), but exchangeable calcium has more recently been shown to have very strong predictive powers for SOC content in water limited grassland ecosystems (Rasmussen et al., 2018). This is due to the formation of organo-mineral complexes, which can physically occlude SOC from microbes, therefore preventing its decomposition (Baldock and Skjemstad, 2000). In grasslands, this is primarily seen in the formation of stable aggregates typical of the Chernozemic Ah horizon. These complexes and aggregates can remain in the soil protecting SOC for millennia (Zhang, 1994; Brodowski, 2006; Craine, 2010). Stabilization and protection of C in the soil are also affected by soil water content (Craine, 2010). Without enough water in the soil, as is typically the case in the grassland ecosystems in BC, microbial activity can be drastically reduced. Water limited soil conditions can also physically prevent microbes from reaching SOM, further protecting it from decomposition. Stabilization of SOC can also be achieved by Ca^{2+} ions through their bridging role in which Ca^{2+} ions are electrostatically bound to both the negative surfaces on SOM and surfaces of mineral particles (e.g., phyllosilicates) (Rowley, 2018). This bridging helps initiate flocculation, consequently leading to aggregate formation and physical protection of SOM within the aggregates (Gaiffe, 1984; Shipitalo and Protz, 1989). This role of Ca^{2+} ions is pH dependent, needing a more alkaline soil pH. Grasslands of BC are both rich in Ca^{2+} ions and typically have alkaline pH, making this an important process in the protection of SOC in these ecosystems.

Organic matter accumulation, as a typical soil formation process of Chernozems, is affected by multiple factors such as the initial composition of organic matter input, reactions of organic compounds with mineral surfaces, soil texture and pH, available soil water, and the presence and activity of soil organisms. How soil C stocks change over time is also a product of multiple factors, and long-term follow up studies are needed to better understand it. Lac du Bois Grassland is an ideal place to carry out these long-term follow up studies in BC, as this area has been a site of numerous studies and detailed documentation since the 1940s.

1.3 Lac du Bois Grassland: A Case Study for the Grasslands of BC

Since the initial studies in 1947 and 1961 (Tisdale, 1947; van Ryswyk et al., 1966), Lac du Bois Grassland has been intensively studied. Historic soil C stock, plant community and other various in soil and vegetation properties have been recorded and are available from those initial studies, allowing for long-term comparisons. In addition, the Lac du Bois Grassland has many characteristics typical of the Southern Interior grasslands of BC. This semi-arid, shrub-steppe ecosystem spans from the valley bottom in the Bunchgrass BEC to the Interior Douglas-fir (IDF) biogeclimatic zone at the elevation of about 1,000 m a.s.l., encompassing the range of elevations at which grasslands typically occur in the Southern Interior of BC. It is also representative of the changes in rangeland management practices in BC spanning from severe overgrazing to seasonal differed moderate grazing.

The Lac du Bois Grassland was established as a Protected Area in 1996 by the BC Parks to protect this area's unique mix of grassland and forest ecosystems located just north of Kamloops, BC. This area is at the Northern most reaches of the Palouse prairie and PNB grasslands, considered as one of the rarest and most endangered grasslands in the world (Noss et al., 1995; Samson & Knopf, 1994; Endress et al., 2020). All of this makes the Lac du Bois Grassland a unique study site, worthy of the follow up examination 58 years after the initial study of van Ryswyk et al. (1966).

According to the initial description of the Lac du Bois Grassland carried out by van Ryswyk et al. (1966), over a distance of 10 km spanning through a 600 m elevation gradient, the following three distinct soil great groups of the Chernozemic order are present: Brown (350 to 610 m), Dark Brown (610 to 825 m), and Black Chernozems (825 to 975 m). The study by van

Ryswyk et al. (1966) also found that across this gradient, SOC and precipitation increase with elevation, while air temperature decreases. Furthermore, each soil great group has been associated with its own distinct plant community (Tisdale, 1947; van Ryswyk et al., 1966). Dark Grey Chernozems, the fourth Chernozemic great group, would typically be present at the transition between grassland and forest ecosystems with greater effective precipitation, but soils at the elevation above 975 m at the Lac Du Bois grassland are more commonly described as Eutric Brunisol or Brunisolic Gray Luvisols due to high rainfall interception and rapid soil water use by vegetation (Sanborn and Pawluk, 1983). Therefore, my study is concentrated on the Brown, Dark Brown, and Black Chernozemic great groups and their associated plant community.

Plant communities at the Lac du Bois Grassland were first described by Dr. Edward Tisdale (1947), who noticed the distinct plant community transitions in this area that corresponded to a distinct soil type. Three plant communities described by Tisdale (1947) were: (i) *Agropyron-Artemisia* or Lower Grassland Zone, (ii) *Agropyron-Poa* or Middle Grassland Zone, and (iii) *Agropyron- Festuca* or Upper Grassland Zone, which were associated with Brown, Dark Brown, and Black Chernozem soil types, respectively. This initial research was furthered by van Ryswyk et al. (1966) who, in 1961, carried out a more extensive description of associated soil types and climate variables with respect to the present grassland condition in these zones, rather than the potential grassland community as described by Tisdale (1947). The study by van Ryswyk et al. (1966) determined that temperature and precipitation effectiveness best described the associated differences in SOC and relatively sharp boundaries between the grassland zones originally identified by Tisdale (1947). Studies describing the transition between Chernozemic great groups and associated C storage across a landscape have been carried out on the Canadian prairies in recent times (Landi et al., 2003), but not here at Lac du Bois. Since those early studies by Tisdale (1947) and van Ryswyk et al. (1966), numerous other studies, focused on soil and plant communities, have been conducted at the Lac du Bois Grassland (e.g., McLean and Marchand, 1968; Watson, 1977; Jakoy, 1981; Carlyle et al., 2011; Evans et al., 2012; Krzic et al., 2014; Lee et al., 2014; Cumming et al., 2016; Bradfield et al. 2021) contributing to better understanding of this unique area while describing the present state of the plant communities over a wide area of the grassland area.

It is also important to note that the Lac du Bois Grassland is representative of the changes in rangeland management practices in BC. The Canadian Pacific Railway was completed in the late 1800s, permanently establishing the cattle industry in BC by early 1900s. This resulted in heavy grazing on grasslands throughout the BC Interior, including the Lac du Bois Grassland. This overgrazing came to a head in the droughts of the 1930s (van Ryswyk et al., 1966). Year-long grazing in the open grassland was no longer an option by 1935, forcing cattle and horses to graze in the forested rangeland, allowing for some grassland recovery (Tisdale and McLean, 1957). From 1940 to 1965, sheep grazing helped further recovery of the grassland, but was then followed by year-long cattle grazing from 1965 to 1974 that once again caused severe deterioration (Watson, 1977). Since 1975, seasonally differed moderate cattle grazing has helped with grassland recovery (Campbell and Bawtree, 1998). Grazing pressure varies across the grassland, with the lower grassland having the lowest grazing pressure due to its steeper terrain, more arid conditions and reduced aboveground biomass. Improved grassland management does not only lead to higher forage productivity, but it can also result in an increased C sequestration, and consequently healthier grasslands (Conant et al., 2017).

Grazing history and trends in weather are important drivers of plant community composition and need to be considered when evaluating the health and productivity of present plant communities. During the early 1960s, plant communities within the three zones were described by van Ryswyk et al. (1966) and results are summarized with the dominant species in each zone (Table 1-1). The middle and upper grassland areas were dominated by species characteristic of early- and mid-seral stage. In particular, needle-and- thread grass and Sandberg's bluegrass had the highest cover and frequency over all other recorded species in the middle grassland. In contrast to what is now the dominant plant species in this zone (Lee et al., 2014), bluebunch wheatgrass had a cover of only 3% and occurred in only 10% of the sampling plots over the study area. Similarly, van Ryswyk et al. (1966) reported that rough fescue was not present in the dry (825-915 m) portion of the upper zone but did record low cover and frequency values of 6 and 17%, respectively, in the moist zone (915-975 m) of the upper grassland (Table 1-1). Rough fescue was displaced in the upper grassland by bluebunch wheatgrass (44/90%) and Sandberg's bluegrass (10/67%) in the dry zone. There was a variety of species in the moist section of the upper grassland with the leading species being Kentucky bluegrass with cover and frequency of 42 and 87%, respectively. Only the lower grassland area had the distribution and cover of species that we would now consider representative of a late-seral plant community at this elevation (Gayton, 2004; Lee et al., 2014). The plant community in the lower grassland area was likely a reflection of the steep topography and limited access to water that would lead to low grazing pressure.

Table 1-1 Summary of plant species cover / frequency (%) measured by van Ryswyk et al. (1966) in the lower, middle, and upper dry and moist elevation zones of the Lac du Bois grassland area.

Zone	Historical scientific name	Common name	Cover / frequency (%)
Lower (345-610 m)	*Agropyron spicatum*	Bluenbunch wheatgrass	46 / 87
	Artemisia tridentata	Big sagebrush	18 / 54
	Poa secunda	Sandberg's bluegrass	18 / 93
Middle (610-825 m)	*Stipa comata*	Needle and thread grass	66 / 100
	Poa secunda	Sandberg's bluegrass	17 / 95
Upper (825-975 m)			
Dry (825-915 m)	*Agropyron spicatum*	Bluenbunch wheatgrass	44 / 90
	Poa secunda	Sandberg's bluegrass	10 / 67
Moist (915-975 m)	*Poa pratensis*	Kentucky bluegrass	42 / 87
	Agropyron spicatum	Bluenbunch wheatgrass	20 / 33
	Astragalus miser	Timber milk-vetch	19 / 68
	Stipa columbiana	Columbia needlegrass	18 / 58
	Festuca scabrella	Rough fescue	6 / 17

Almost six decades after the study by van Ryswyk et al. (1966) at the Lac du Bois Grassland, reassessment of the factors that were identified to affect the distribution of Chernozemic great groups was made possible by a LiDAR derived digital elevation model, more detailed climate measurements, and more advanced laboratory analytical methods including those focused on soil C fractionation. Due to the close spatial proximity of the three (out of four) Chernozemic great groups and existence of detailed description of plant composition and soil properties from 1961, the Lac du Bois Grassland provides an ideal case study for evaluation of the soil and plant zonation. Findings of my study will provide information about the long-term (58 years) changes in SOC and plant communities in bunchgrass grassland ecosystems. Such findings are of importance for climate change predictions, especially since it is expected that bunchgrass grasslands are to experience more varied patterns of precipitation and a 4°C increase in annual temperature in next 100 years (Canadian Climate Change Scenarios Network, 2011).

1.4 Study Objectives

This study will be guided by the following objectives.

(1) Determine topographic, microclimate and soil variables that affect the distribution of Chernozemic great groups and associated soil C (i.e., total, organic, active C) and plant communities over an elevation gradient at the Lac du Bois Grassland.

(2) Using 2019 topographic, microclimate and soil variables, reassess boundaries of three Chernozemic great groups (and associated soil C and plant communities) as established in 1961 by the study of van Ryswyk et al. (1966).

Study objectives 1 and 2 are addressed in Chapter 2 of this thesis.

Chapter 2. Elevation Gradient Drives Distribution of Chernozemic Great Groups, Soil Carbon and Plant Communities in a Semiarid Grassland in British Columbia

2.1 Introduction

Grassland ecosystems provide many ecosystem services such as soil carbon (C) storage, livestock grazing, high biodiversity and space for recreation. Since it has been estimated that grasslands contain up to 30% of terrestrial C (Follett, 2000), soil C sequestration in these ecosystems has become a topic of great interest as the global community becomes more aware and concerned of climate change. This is of a particular interest for countries, like Canada that have large areas under grasslands.

The vast majority of Canadian grasslands are in the Prairie provinces (Pennock et al., 2011), and only about 9500 km^2 of grasslands are to be found in British Columbia (BC) (Wikeem et al., 1993). Unlike the mixed grass prairies in Alberta, Saskatchewan and Manitoba, which have developed under the influence of large bison herds and periodic severe trampling, bunchgrass-dominated grasslands in BC have developed under the low-intensity grazing of wild ungulates such as elk, deer and bighorn sheep (Mack and Thompson, 1982). Grasslands of BC are also characterized by dominance of cool season C_3 grass species since these ecosystems receive much of their moisture in the spring from snow melt and almost no rainfall over the summer months. The Prairie grasslands, on the other hand, are comprised of a mix of cool season C_3 grasses growing early in the season and C_4 grasses dominating in the prime growing summer months, as there is still enough of the soil water to maintain their growth and more frequent summer precipitation (Barnes and Harrison, 1982; Barnes et al., 1983).

Most of BC's grasslands are associated with an undulating topography with significant elevation changes over short distances, which in turn leads to a diverse microclimate, plant communities and soil types. Majority of grasslands in BC are located in the valleys of the Southern Interior, and the Lac du Bois Grassland, located just north of Kamloops, has many characteristics typical of the grasslands in this part of the province. According to the Biogeoclimatic Ecosystem Classification (BEC), the Lac du Bois Grassland extends from the valley bottom at about 400 m above sea level (a.s.l.) in the Bunchgrass to the Interior Douglas-fir (IDF) biogeoclimatic zone at an elevation of about 1,000 m a.s.l., encompassing the range of elevations at which grasslands typically occur in the Southern interior of BC. It is also representative of the changes in rangeland management practices in BC that ranged from severe overgrazing to seasonal differed moderate grazing. Additionally, soil and vegetation of the Lac du Bois Grassland have been extensively studied ever since the initial study by Tisdale (1947) followed by the seminal study by van Ryswyk et al. (1966) and numerous other studies (McLean and Marchand, 1968; Watson, 1977; Jakoy, 1981; Carlyle et al., 2011; Evans et al., 2012; Krzic et al., 2014; Lee et al., 2014; Cumming et al., 2016; and Bradfield et al., 2021). All of this positions the Lac du Bois Grassland as a unique study site suitable for long-term follow up evaluations of soil properties and plant communities distributed over its elevation gradient. The Lac du Bois Grassland also provides a unique opportunity to evaluate current criteria of the Canadian soil classification system for differentiation among the great groups of the Chernozemic soil order.

Chernozems of BC differ from the Chernozems of the Prairie provinces, region that served as the basis for the development of criteria used to differentiate among the great groups of the Chernozemic order. Studies describing the transition between Chernozemic great groups and associated C storage across a landscape have been carried out on the Canadian prairies in recent times (Landi et al., 2003), but these are lacking in BC. Hence, Chernozems found in BC, characterized by different plant communities and moisture regime, provide an opportunity to potentially refine criteria used to differentiate among the great groups of this important soil order. Transitions of the three distinct plant communities and their associated distinct soil types have been first described by Tisdale et al. (1947). This research was furthered by van Ryswyk et al. (1966) who, in 1961, carried out a more extensive description of the plant communities and associated soil types and investigated the reasons for the relatively sharp boundaries between the grassland zones originally identified by Tisdale (1947). The study by van Ryswyk et al. (1966) determined that the effects of temperature and precipitation effectiveness best described the boundaries between grassland zones and associated differences in soil organic C (SOC) and plant communities.

With 58 years (1961 to 2019) since the measurements on the elevational transect study by van Ryswyk et al. (1966) at Lac du Bois Grassland, there is a need to follow up on this influential study as grassland condition has been greatly improved due to adoption of better grazing management and extensive collaboration among all users of this grassland area. Identifying management practices that increase soil C storage and plant species biodiversity following restoration of degraded ecosystems are of great importance as the impacts of a warmer climate from rising CO_2 concentrations becomes more and more evident around the globe.

Following the same criteria van Ryswyk et al. (1966) used to select sample locations along the elevation gradient, my study set out to refine which topographic, microclimate and soil variables affect the distribution of the three Chernozemic great groups, soil C, and plant communities at Lac du Bois Grassland. The objectives of this study were to:

The objectives of this study were to:

(1) Determine topographic, microclimate and soil variables that affect the distribution of Chernozemic great groups and associated soil C (i.e., total, organic, active C) and plant communities over an elevation gradient at the Lac du Bois Grassland.

(2) Using 2019 topographic, microclimate and soil variables, reassess boundaries of three Chernozemic great groups (and associated soil C and plant communities) as established in 1961 by the study of van Ryswyk et al. (1966).

2.2 Materials and Methods

2.2.1 Study Site

The study was conducted in the spring and summer of 2019 at the Lac du Bois Grasslands Protected Area located just north of the city of Kamloops, BC (50°43'36.6"N 120°26'22.0"W). The Lac du Bois Grassland spans an elevation gradient from 400 to 1000 m above sea level (a.s.l.), with forest ecosystems extending beyond 1000 m (a.s.l.). It is located in the Thompson-Okanagan Region just west of the North Thompson River and north of the South Thompson River.

As the last glaciation was ending, much of the Thompson and Nicola valleys were dammed by remnant ice, causing the formation of glacial lakes and large fine textured deltas (van Ryswyk and McLean, 1989). Once this remaining ice melted, these deposits dried and were spread by wind across the lower elevations of these valleys leaving a silty cap across the valley bottom up to 550 m in elevation (Watson, 1977; van Ryswyk and McLean, 1989). The Glacial activity on Lac du Bois also resulted in an undulating topography, dominated by till plains and drumlin till plains (Fulton, 1975). The parent material in this location is an ablation till with basic volcanic and limestone bedrock, with this aeolian veneer that formed the A horizon (Young et al., 1992). The soils in the Lac du Bois Grassland are sandy loams to loams (Young et al., 1992). The Lac du Bois Grassland has southern exposure, with slopes ranging from 2 to 20°.

Lac du Bois Grassland is classified as a dry steppe ecosystem (Carlyle et al., 2011; White et al., 2000) located in the interior dry belt of BC and the Montane Cordillera Ecozone. Daubenmire (1970) referred to this area as the most northern reaches of the Palouse Prairie and more recently the area has been described as the Pacific Northwest Bunchgrass ecosystem (Endress et al., 2020), which extends from central Oregon, across Washington, Idaho and parts of western Montana. Studies by Tisdale (1947), van Ryswyk et al. (1966) and McLean and Marchand (1968) described three grassland zones (lower, middle and upper grassland), each with distinct plant communities and soil types. In the lower grassland (LG), the mean annual precipitation (MAP) is 270 mm, and the mean annual temperature (MAT) is 8.9°C. The LG is in the Thompson Very Dry Hot Bunchgrass Variant (BGxh2) (Ryan et al., *in press*). The middle grassland (MG) is in the Very Dry Warm Bunchgrass Variant (BGxw1) (Ryan et al., *in press*). The MAP increases by ~100 mm and the MAT decreases by 3°C in the upper grassland (UG) that has been typically classified as part of the Very Dry and Hot Interior Douglas-fir (IDFxh2) sub-zone (Hope et al., 1991; Ryan et al., *in press*). This climatic difference over the elevation gradient also causes a difference in potential evapotranspiration for the month of July from 216 mm month^{-1} in the LG to 186 mm month^{-1} in the UG.

The differences in microclimate also lead to different plant communities and different Chernozemic great groups across the elevation gradient. As reported by Young et al. (1992), in the LG (350 – 610 m a.s.l.), the soil is a Brown Chernozem, with bluebunch wheatgrass [*Pseudoroegneria spicata* (Pursh) A. Löve] and big sagebrush [*Artemisia tridentata* (Nutt.)] as the dominant vegetation. The MG (610 – 825 m a.s.l.) is located on a Dark Brown Chernozem, with Sandberg's bluegrass (*Poa secunda* L.) and bluebunch wheatgrass as dominant plant species. The UG (825 – 1000 m a.s.l.) is located on a Black Chernozem, with rough fescue [*Festuca campestris* (Rydb.)] as the dominant species. Dark Grey Chernozems, the fourth Chernozemic great group, are not commonly described in the open grassland or forested area at Lac du Bois and therefore was not included in my study. Any reference to the three Chernozemic great groups will be referring to the open grassland great groups described above.

2.2.2 Sampling and Analysis

Sampling

In spring of 2019, potential sampling sites were located in the GIS using a LiDAR derived digital elevation model (DEM) with a 3 × 3 m cell size according to the same criteria van Ryswyk et al. (1966) used in their study as follows: (i) slope 10 - 20°, (ii) a slope length of ≥10 m (iii) no curvature, and (iv) a south facing aspect. The total elevation change of the study area was 600 m and potential sampling locations were further stratified so that there was a site selected every 25 m in elevation gain for a total of 24 unique elevation bands from 400 to 1000 m (a.s.l.). Sample sites were then randomly located in the field using a map of potential locations as selected by the topographic criteria listed above. Specific sampling locations within each elevation band (n=24) were then selected where plant species composition and cover were representative of the broader area and there was also adequate vehicle access for moderate hikes to and from the roadside. Rock outcrops, old roadways, and specific areas of the grassland with obvious signs of human or livestock disturbance were also avoided when selecting sample locations. Two additional sites were selected from the 600 and 625 m a.s.l. elevation bands when accessibility above these elevations became problematic and the linear transect across elevation bands was shifter slightly to the east (red points, Fig. 2-1), resulting in total of 26 sampling sites at the Lac du Bois Grassland (red points indicate 26 sampling sites and yellow boxes indicate 5 weather stations). Green shading represents the area that satisfied topographic restrictions, and 26 sampling sites were picked from those areas.

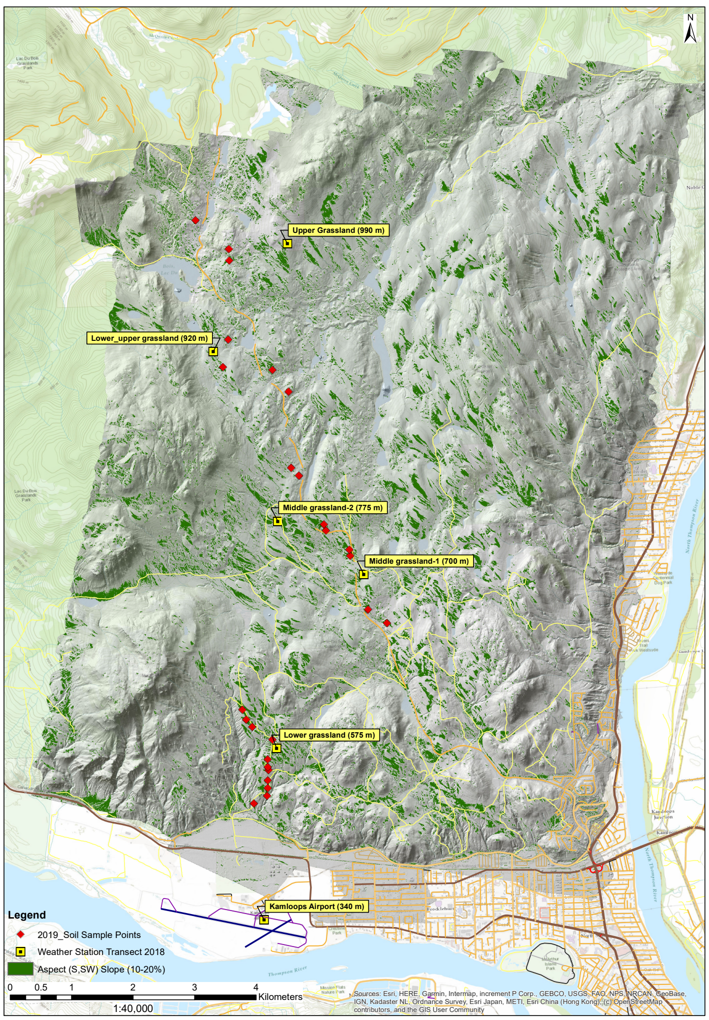

Figure 2-1. LiDAR generated 3-m resolution digital elevation model of Lac du Bois Grassland (red points indicate 26 sampling sites and yellow boxes indicate 5 weather stations). Green shading represents the area that satisfied topographic restrictions, and 26 sampling sites were picked from those areas.

Sampling occurred at each of the 26 sites across the elevation gradient between May 1st and May 28th, 2019. At each of 26 sites, two subsamples were taken 5 to 10 m apart, using an undisturbed soil core from 0-5, 5-15, and 15-30 cm depths for a total of 52 unique soil profiles being sampled. These samples were used to determine bulk density, coarse fragment content, total soil C, total N, organic C, inorganic C, active C comprised of permanganate oxidizable C (POXC) and dilute acid extractable polysaccharides (DAEP), pH, and colour. These samples allowed me to address the study objective 1.

To be able to compare data from this study to those obtained by van Ryswyk et al. (1966), or in other words to address the study objective 2, weather data from 2017 through 2020, vegetation, and soil pit descriptions located at each of the five weather stations data were collected in 2019. Weather stations were installed at similar elevations and locations to the weather stations that were established in 1961 by van Ryswyk et al. (yellow boxes in Fig. 2-1). One weather station is located in the LG (575 m a.s.l.), two in the MG (711 and 790 m a.s.l.), and two in the UG (917 and 980 m a.s.l.). Four of those weather stations were established in May 2017, while the station at 917 m (a.s.l.) was established in April 2018. These stations allowed measurements of precipitation, air temperature, and relative humidity using sensors and instruments developed by the METER Group (Pullman WA, USA). Monthly precipitation effectiveness (P/E) ratio was calculated using Thornthwaite's equation (Thornthwaite, 1931):

$$P/E = 115[(\text{precip. (in.)})/(\text{Temp. } (^{\circ}\text{F} - 10))]^{10/9}$$

One soil pit was excavated at each of the five weather stations (Fig. 2-1) to a depth that was deep enough to clearly expose the C horizon (> 80 cm). The horizons were delineated and soil samples were taken from the centre of each horizon. These samples were dried in the force-air oven at 50°C until mass loss stabilized, sieved through a 2-mm sieve and used to determine total soil C, total N, organic C, inorganic C, exchangeable cations, cation exchange capacity, extractable nutrients, pH, total sulphur (S), organic phosphorus (P), available P and texture.

Soil Bulk Density and Particle Analysis

Fine fraction soil bulk density was determined on undisturbed core samples taken from the 0-5 cm, 5-15 cm and 15-30 cm depths at 26 study sites. Soil bulk density was calculated on a coarse fragment-free basis as the mass of dry soil per volume of field-moist soil (Blake and Hartge, 1986). The 0-5 cm sample was taken using a single-cylinder drop-hammer sampler core (35.5 cm^3). Due to the small size of this core, five cores were taken within a 30 × 30 cm area to create a composite sample (177.5 cm^3 total) that would ensure enough sample was collected to complete all analyses. Soil bulk density was calculated from this composite as fine fraction (<2 mm) dry mass over volume (177.5 cm^3). The samples from 5-15 cm and 15-30 cm depths were taken using one double-cylinder, drop-hammer sampler, with a 7.5-cm diameter by 7.5-cm deep core (331.35 cm^3). These samples were dried in the force-air oven at 50ºC until the mass stabilized and sieved through a 2-mm sieve. The volume of coarse fragments was determined using a particle density of 2.65 g cm^{-3} and their dry mass. Soil bulk density values were used to calculate C stocks as described below.

Soil particle size was determined at all soil horizons of each soil pit and the 0-15 and 15-30 cm soil depths at six elevations (every 100 m) across the study gradient. The hydrometer method following Karla and Maynard (1991) was used. Soil samples (50 g) without any pre-treatment for organic matter or carbonates were dispersed using 100 ml $Na_6(PO_3)_6$ (hexametaphosphate 50 g L^{-1}) and 100 ml distilled H_2O and agitated on a bench-top shaker for 16 hours. Dispersed samples were then transferred to sedimentation tubes and filed to 1000 ml with distilled H_2O. A standard hydrometer (ASTM 151H) was then used to determine particle size (Silt+Clay) at 40s and 2 hours (Clay). Soil samples with high organic matter content needed pre-treatment and particle size analysis was carried out on soil pit horizon samples off site.

Soil Carbon Fractions

Total soil C and N, inorganic C, active C (i.e., POxC and DAEP) were determined on soil samples collected for bulk density determination from all depths and each sub-sample at each of the 26 sites. Prior to analysis, soils are ring ground to <1mm and total C and N are determined by dry combustion (Nelson and Sommers, 1996) using a Flash 2000 elemental analyser (Thermo Fisher Scientific, Waltham, MA, USA). Soil inorganic C (SIC) was determined using a Primacs SNC-100 analyzer (Skalar, The Netherlands) that acidifies the sample using phosphoric acid and collected CO_2 is then measured using an IR detector. Soil organic C (SOC) is calculated as the difference between total C and SIC.

POXC was determined by method of Weil et al. (2003) and the detailed procedure by Culman et al. (2012) using a microplate spectrophotometer (TECAN Group Ltd., Zurich, Switzerland) at 550 nm to determine absorbance. Detailed description of this method can be found in the appendix.

DAEP were determined using the phenol-sulfuric acid method for labile polysaccharide analysis described by Lowe (1993). The absorbance of the samples was read at 490 nm with a microplate spectrophotometer (TECAN Group Ltd., Zurich, Switzerland). Additional details about this method can be found in the appendix.

Carbon Stock

Carbon stocks (kg of SOC m^{-2}) were calculated from the 0-30 cm soil layer, using the following equation:

$$SOC_{kg/m^2} = SOC_{\frac{g}{g}} * FF\ Bulk\ Density_{\frac{kg}{m^3}} * Depth_{\ m} * (1 - Coarse\ Fragment\ Content_{\frac{m^3}{m^3}})$$

This calculation offers a SOC stock that is scalable to larger areas for the same depth. On rocky soils such as those found at Lac du Bois grassland, correcting for coarse fragment content (CFC) is extremely important. Without this step, calculation of the C stock would assume that the 0-30 cm layer is comprised exclusively of the fine fraction soil, and therefore over estimating SOC stock. To the best of my knowledge, a similar approach in calculating soil C stock was used by van Ryswyk et al. (1966), although methods for SOC determination and calculated depth and volume units did differ between our studies. The unit calculated by van Ryswyk et al. (1966) was $SOC_{g/2dm^3}$ which was interpreted as SOC_{g/dm^2} in the top 2 decimeters of soil ($SOC_{\frac{g}{2dm(dm^2)}} = SOC_{\frac{g}{2dm^3}}$). Therefore, the equation used to calculate SOC_{g/dm^2} in the top 20 cm of soil was:

$$SOC_{g/dm^2} = SOC_{\frac{g}{g}} * FF\ Bulk\ Density_{\frac{g}{cm^3}} * Depth_{\ cm} * \frac{100cm^2}{1dm^2} * (1 - CFC_{\frac{m^3}{m^3}})$$

Soil Chemical Properties

Soil pH was determined on soil samples used to determine bulk density. Soil pH was measured in water (1:1 soil to water) and 0.01 mol L^{-1} $CaCl_2$ (1:2 soil to $CaCl_2$) (Hendershot et al., 2007). Exchangeable cations and cation exchange capacity (CEC) were determined using 0.2 *M* $BaCl_2$ solution extractions (Hendershot and Duquette, 1986; USEPA Method 200.7, 1994) and analyzed using ICP-OES (inductively coupled plasma, optical emission spectroscopy). Electric conductivity was determined using the saturated paste method (Karla and Maynard, 1991).

Mehlich III extraction (Mehlich, 1984), followed by ICP-OES analysis was used to determine extractable nutrients. Total S was measured using microwave acid digestion (Karla and Maynard, 1991), where all S is brought into solution through digestion and all none-sulfate forms are oxidized into sulphate (SO_4^{2-}). This sulphate is then measured using ICP-OES analysis. Organic P was analyzed using acid extraction (Turner et al., 2005) following combustion in a muffler furnace to remove other organic materials. Organic P levels were then measured using ultraviolent light analysis. Available phosphorus was determined using the Bray P-1 extraction method (Bray & Kurtz, 1945; Karla and Maynard, 1991).

Soil Colour

Soil colour was determined on soil samples used to determine soil bulk density. The Munsell Colour System (Lynn and Pearson, 2000) was used to determine the colour value and chroma on dry and field moist samples. These parameters were then used to determine the Chernozemic great group based on the soil colour criteria specified by the Soil Classification Working Group (1998).

Aboveground Biomass and Plant Composition

In June 2019, green standing biomass was determined at the five weather stations sites spread across the elevation gradient. At each of these sites, green standing biomass was clipped as close to the soil surface as possible within four 1-m^2 frames. The biomass was then oven-dried at 60° C for 24 hr and weighed to determine dry aboveground biomass (kg ha^{-1}). Additional biomass data collected from the same locations at peak productivity using the same methods were included in the analysis.

Plant composition was assessed using canopy cover sampling (Daubenmire, 1959) at each of the weather stations and soil pit descriptions. Canopy cover (percent) of individual plant species and three cover types (mineral soil, macrobiotic crust, litter) was estimated within a total of 50 Daubenmire frames (0.2 m × 0.5 m) located randomly along five 50-m transects (10 per transect). Shrub (*Artemisia tridentata*) cover was determined using the intercept method along each transect, determining the percent of the transect covered by shrubs over each of the five 50-m transects.

2.3 Results and Discussion

2.3.1. Topographic, Microclimate, and Soil Variables Effects on Soil C and Chernozemic Great Group Distribution

Weather

Weather data was collected from 2017-2019. The decreasing temperature with an increasing elevation across the Lac du Bois grassland can be seen in Table 2-1. During all growing season months (i.e., April to October), monthly mean temperature was 2.6°C higher at the weather station at the lowest elevation (575 m) relative to the weather station at the highest elevation (980 m) (Table 2-1). Conversely, precipitation increased across the same elevation gradient with the April to October total increasing from 10.0 cm at the lowest site to 29.5 cm at the highest (Table 2-1).

Precipitation effectiveness (P/E), which takes into account both air temperature and precipitation, showed a marked increase over the elevation gradient. The average monthly P/E ratio from April to October at the weather station in the Brown Chernozems is 0.85, less than 1/3 of the average P/E ratio in the Black Chernozems which was 3.12 (at 917 m elevation) and 3.14 (at 980 m elevation) (Table 2-1). The P/E ratio in the Dark Brown Chernozem was 2.19 at both 711 m and 790 m elevation, which was just over 2/3 of the PE ratio in the Black Chernozems (Table 2-1). This stepwise increase in P/E from near 1 in the Brown Chernozems, to 2 in the Dark Brown Chernozems, to 3 in the Black Chernozems shows the power of this variable in differentiating Chernozemic great groups. This three-step increase is also mirrored in the precipitation and air temperatures.

Although all weather stations were relatively evenly spaced apart (at 575 m, 711 m, 790 m, 917 m, and 980 m a.s.l.), there was much less variation in recorded weather variables among the weather stations located in the same Chernozemic great groups compared to those that were located in different great groups (Table 2-1). van Ryswyk et al. (1966) determined P/E to be the most useful variable to determine the distribution of Chernozemic Great Groups as well. A study by Thornthwaite (1931) determined the range in P/E ratios for certain soil types. According to the measured P/E for Brown and Dark Brown Chernozems these soils can be classified as “Chestnuterths”. Measured P/E from the Black Chernozem zone classified these soils as “Blackerths” (Thornthwaite, 1931). Chestnuterths and Blackerths are early nomenclature that

Table 2-1. Three-year average (2017-2019) monthly mean maximum, mean minimum, mean temperature, precipitation, and precipitation effectiveness from April to October across the 400 to 1000 m elevation gradient at Lac du Bois Grassland.

Soil Great Group (elevation)	Apr	May	Jun	Jul	Aug	Sep	Oct	Avg. Apr to Oct
				Monthly mean max. temperature (°C)				
Brown (575m)	14.2	22.9	24.9	29.1	29.0	20.9	11.8	21.8
Dark Brown (711m)	13.3	22.6	24.7	28.3	28.9	20.1	11.1	21.3
Dark Brown (790 m)	12.6	22.6	22.7	27.0	27.3	18.8	10.5	20.2
Black (917 m)	10.8	20.3	20.1	23.7	24.4	16.1	8.9	17.8
Black (980 m)	10.5	18.9	20.3	25.0	25.4	17.2	8.8	18.0
				Monthly mean min. temperature (°C)				
Brown (575m)	2.3	9.1	11.1	13.7	13.5	9.4	2.1	8.7
Dark Brown (711m)	1.5	7.3	9.1	11.8	11.8	7.9	0.7	7.2
Dark Brown (790 m)	1.3	8.5	9.3	12.2	12.3	8.0	0.9	7.5
Black (917 m)	-1.1	7.3	8.1	10.5	10.4	6.1	-0.5	5.8
Black (980 m)	1.0	8.1	9.1	12.7	13.1	7.9	1.1	7.6
				Monthly mean temperature (°C)				
Brown (575 m)	8.0	16.0	17.9	21.4	21.0	14.6	6.5	15.1
Dark Brown (711m)	7.2	14.9	16.5	19.9	19.6	13.4	5.5	13.8
Dark Brown (790 m)	6.8	15.7	15.9	19.7	19.6	13.0	5.4	13.7
Black (917 m)	4.8	14.0	14.1	17.2	17.2	10.6	3.7	11.7
Black (980 m)	5.4	13.3	14.3	18.7	19.0	12.1	4.7	12.5
				Precipitation (cm)				
Brown (575 m)	0.33	1.69	1.13	1.21	1.34	2.23	2.01	10.03
Dark Brown (711 m)	3.30	2.85	2.69	2.95	2.01	3.78	3.98	21.57
Dark Brown (790 m)	3.04	0.96	2.74	3.40	2.49	4.93	3.87	21.43
Black (917 m)	0.67	1.97	4.27	4.28	3.20	8.08	5.28	27.75
Black (980 m)	1.02	3.31	5.52	4.09	3.30	6.89	5.39	29.52
				Precipitation effectiveness (P/E) ratio				
Brown (575 m)	0.22	0.93	0.55	0.53	0.60	1.34	1.78	0.85
Dark Brown (711 m)	2.97	1.74	1.53	1.50	0.99	2.54	4.04	2.19
Dark Brown (790 m)	2.77	0.50	1.60	1.77	1.25	3.47	3.95	2.19
Black (917 m)	0.58	1.20	2.82	2.50	1.81	6.71	6.24	3.12
Black (980 m)	0.90	2.20	3.72	2.25	1.75	5.24	5.96	3.14

was used before the Canadian System of Soil Classification was created. Chestnuterths refer to Dark Brown Chernozems while Blackerths refer to Black Chernozems. Both van Ryswyk at al.

(1966) and Thornthwaite (1931) demonstrated the power of P/E as a climactic variable, and we can once again see its ability to differentiate Chernozemic Great Groups in this study.

Vegetation

The lower grassland, originally described as the Artemisia zone by Tisdale (1947), extends from 400 m to about 650 m in elevation. This portion of the grassland has remained relatively unchanged over the 58 years since it was described by van Ryswyk et al. (1966) (Fig. 2-2). The lower grassland is still dominated by *Pseudoroegneria spicata* (all scientific authorities are indicated in Table 2-2), *Artemisia tridentata* and *Poa secunda*. Other species that occurred frequently in the lower grassland were *Antennaria dimorpha, Boechera retrofracta, Castilleja thompsonii*, *Comandra umbellata* and *Erigeron sp.* (Table 2-2). Artemisia shrubs covered much of this area (Table 2-3). Due to its frequency and visual dominance, *Artemisia tridentata* is the species mentioned in the vegetation zone's title for the lower grasslands. The lower grassland has the highest percentage of bare soil, cryptogamic crusts, and exposed rock (Table 2-3). This is also the portion of the Lac du Bois grassland with the least aboveground biomass production (Table 2-4), due to the high air temperatures and low precipitation relative to upper elevations. The lower grassland is also the area with the lowest grazing pressure due to the lack of water, steepness and lower aboveground biomass production.

The middle grassland (vegetation zone *Pseudoroegneria - Poa*) extends from the upper boundary of the lower grassland at 650 m to 800 m in elevation. It was originally described as the *Hesperostipa – Pseudoroegneria* zone by Tisdale (1947) and then changed to the *Hesperostipa – Poa* zone by van Ryswyk et al. (1966). This area is now dominated by *Pseudoroegneria spicata*, with *Poa secunda* and *Artemisia tridentata* being the secondary species (Table 2-2, Fig. 2-2). *Antennaria dimorpha* and *Castilleja thompsonii* were the only other

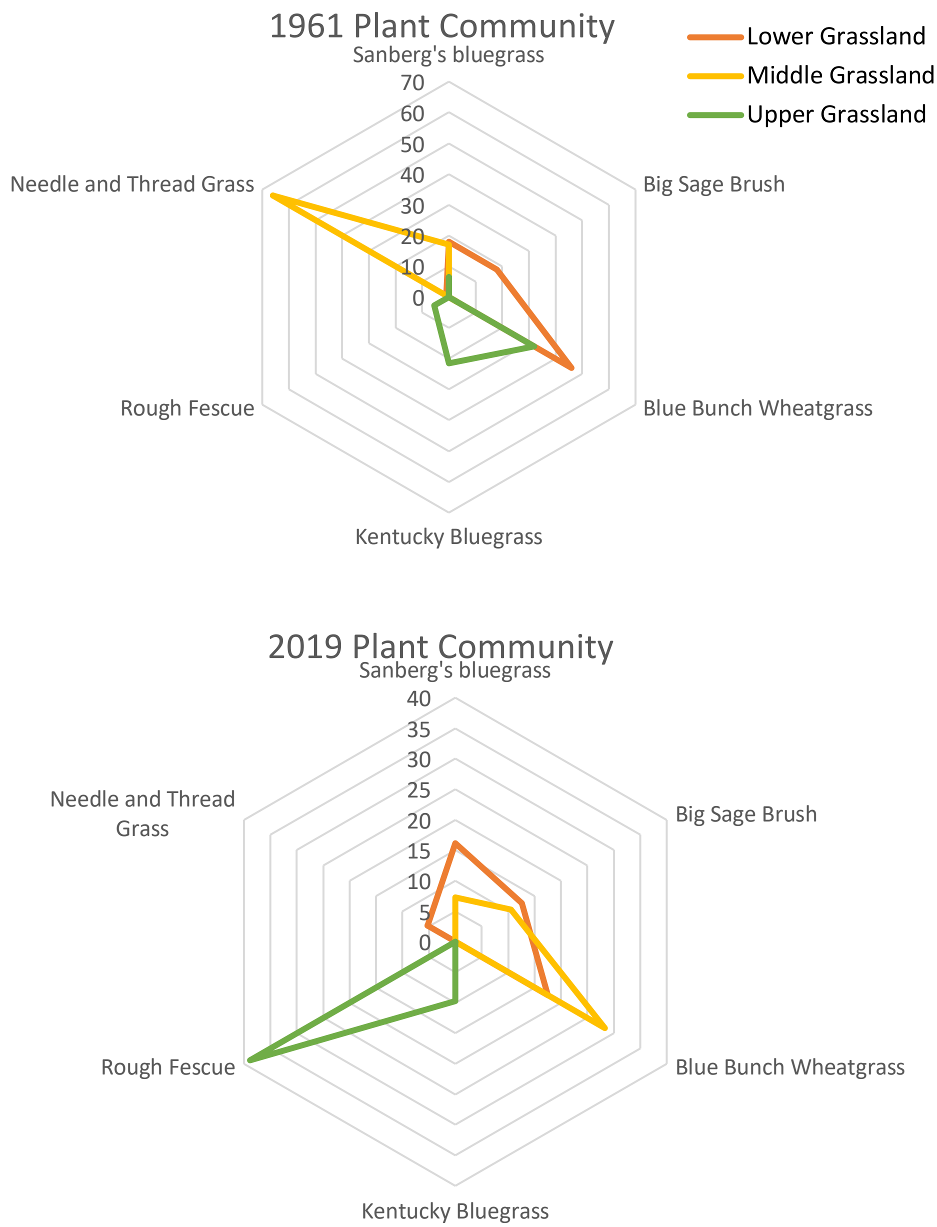

Figure 2-2. Radar graph for percent cover of six major plant species found at Lac du Bois Grassland in 1961 and 2019. Data from 1959-1961 was sourced from van Ryswyk et al. (1966).

species that had significant overlap with the lower grassland (Table 2-2). Other species that occurred frequently in the middle grassland, but not the lower, were *Achillea millefolium,* *Astragalus miser, Collinsia parviflora* and *Koeleria macrantha* (Table 2-2). In the 58 years since van Ryswyk characterized these zones, *Hesperostipa comata* has decreased significantly (Fig. 2-2). Van Ryswyk et al. (1966) suggested the middle grassland vegetation community in 1961 was simply a seral stage indicative of the poor range health, and *Hesperostipa comata* would decrease as *Pseudoroegneria spicata* increased with improvements in grazing regimes and overall grassland health. Plant species composition that I observed in 2019 has confirmed this suggestion, showing a move towards a late seral stage community in the middle grassland at Lac du Bois.

Aboveground biomass of forage species at the middle grassland has increased relative to the lower grassland (Table 2-4), which is to be expected due to higher P/E. This *Pseudoroegneria – Poa* zone is a typical grassland vegetation community for this elevation, although there is more *Artemisia tridentata* than what was originally described by Tisdale (1947). Average shrub cover of *Artemisia tridentata* at the upper range of the middle grassland (790 m) was similar to the lower grassland but was nearly 50% more than what was measured at the lowest sampled position (711 m) of the middle grassland. A result that may be a reflection of recent grazing history as increased presence of *Artemisia tridentata* is a sign of overgrazing (Tisdale, 1947; Tisdale and Hironaka, 1981; Holechek and Stephenson, 1983; Doescher et al., 1990). *Artemisia tridentata* is generally replaced at higher elevations by open grassland or by *Pseudotsuga menziesii* forests (Tisdale, 1947; McLean, 1970). With *Artemisia tridentata* spreading into the middle grassland, and *Hesperostipa comata* decreasing in the middle grassland, this area has become a continuation of the lower grassland with a few differences. The bunchgrass and forb density is higher in the middle grassland than in the lower grassland. The middle grassland also has one third of the bare soil that the lower grassland does (Table 2-3).

Bare soil has been shown to be a useful indicator for both aridity and grazing pressure (Krzic et al. 2014; Lee et al. 2014). The lower grassland is more arid compared to the middle grassland, helping to explain the differences in bare soil and above ground biomass production (Table 2-3 and 2-4).

Table 2-2. Composition and distribution of species that attained a *frequency* of at least 40% at one of the five sites. The left number in each pair represents percent coverage and the right represents percent frequency.

Vegetation Zone	Artemisia tridentata	Poa – Pseudoroegneria		Festuca Campestris	
Elevation (m)	575	711	790	917	980
Chernozemic Great Group	Brown	Dark Brown	Dark Brown	Black	Black
Achillea millefolium L.	0/0	0/0	5/60	0/0	3/44
Achnatherum nelsonii (Scribn.)	0/0	0/0	0/0	18/72	0/0
Antennaria dimorpha (Nutt.) T. & G.	6/18	3/44	5/64	0/0	0/0
Artemisia tridentata Nutt.	13/50	8/14	13/26	0/0	0/0
Astragalus collinus (Hook. ex Hook.) G. Don	0/0	5/48	2/8	0/0	0/0
Astragalus miser Dougl. ex Hook.	0/0	0/0	9/68	14/66	13/46
Boechera retrofracta Hornem.	3/14	2/50	1/22	0/0	0/0
Castilleja thompsonii Pennell	5/34	5/82	3/36	0/0	0/0
Centurea maculosa DC.	0/0	0/0	1/6	8/42	0/0
Collinsia parviflora Dougl. ex Lindl.	0/0	1/44	3/86	0/0	<1/8
Comandra umbellata (L.) Nutt.	3/22	5/44	0/0	0/0	0/0
Erigeron sp. Nutt.	12/44	<1/4	1/14	0/0	0/0
Festuca campestris Rydb.	0/0	0/0	0/0	5/10	73/98
Hesperostipa comata (Trin. & Rupr.) Barkw.	5/20	0/0	0/0	0/0	0/0
Koeleria macrantha (Ledeb.) J.A. Schult. f.	0/0	2/32	5/40	1/14	1/6
Poa pratensis L.	0/0	0/0	0/0	17/64	3/26
Poa secunda L.	16/96	12/100	2/46	0/0	0/0
Pseudoroegneria spicata (Pursh) A. Löve	18/98	21/94	36/100	0/0	0/0
Vicia americana Muhl. ex Willd.	0/0	0/0	0/0	12/46	0/0

The upper grassland (vegetation zone *Festuca campestris*) extends from 800 m to the *Pseudotsuga menziesii* boundary around 1000 m in elevation. This area is dominated by *Festuca campestris* (Table 2-2). *Artemisia tridentata, Pseudoroegneria spicata* and *Poa secunda* no longer appear at this elevation. These three species were dominant in the upper grassland 58 years ago, which indicates that the vegetation in 1961 was a seral stage community. In 2019, the dominance of *Festuca campestris* indicates a progression to a late seral stage community due to improved rangeland management and grazing regimes over the past 58 years. Species that occurred frequently in the upper grassland, but not the middle grassland, were *Centurea maculosa* and *Vicia americana* (Table 2-2). *Achillea millefolium, Astragalus miser* and *Koeleria macrantha* are present in both the middle grassland and the upper grassland (Table 2-2). In the upper grassland, between the bunch and sod forming grasses, very little bare ground or cryptogamic crust can be seen, and near complete vegetation coverage exists (Table 2-2 and 2-3). There is a dramatic switch in vegetation (Fig. 2-2) and biomass production (Table 2-4) between the middle and upper grassland, likely due to the lower air temperatures, increased precipitation, and increased P/E in the upper grassland.

Table 2-3. Average cover of *Artemisia tridentata* (determined through shrub intercept) at five weather stations (at 575 m, 711 m, 790 m, 917 m,, and 980 m above sea level) located across three grassland zones at the Lac du Bois Grassland.

Grassland zone	Lower Grassland	Middle Grassland		Upper Grassland	
Elevation (m)	575	711	790	917	980
Shrub	15	10	16	1	0
Bare Soil	13	5	4	0	0
Cryptogamic Crust	22	43	44	0	4
Rock	10	7	0	0	0

Table 2-4. Forage aboveground biomass, clipped at peak vegetation growth, averaged over 2017-2020 period for three grassland zones at the Lac du Bois Grassland.

Grassland Zone	Average (kg ha^{-1})	Range (kg ha^{-1})
Lower Grassland	966	518 - 1412
Middle Grassland	1091	607 - 1564
Upper Grassland	1700	1521 - 1851

Soils

Similarly to what has been done in the study by van Ryswyk et al. (1966), five soil pits were excavated across the elevation gradient at Lac du Bois in 2019 with an aim to provide detailed description of soil profiles. One soil pit was located in the lower grassland (575 m a.s.l.), while two were located in both the middle grassland (711 and 790 m a.s.l.) and the upper grassland (917 and 980 m a.s.l.). As is typical of Chernozems, all five soil profiles had the same Ah, Bm, Ck sequence of horizons. Chernozemic Ah horizon was 15 cm thick in the lower grassland, and 20-25 cm in the upper and middle grassland (Table 2-5). The pH increased with depth at all sites from near neutral or slightly acidic (pH 6.1-7.4) in the Ah to moderately basic pH (7.3-8.6) in the more calcareous Ck horizon (Table 2-5). The pH of the Ah horizon decreased as elevation increased (Table 2-5). At these 5 sites, soil inorganic C (SIC) was present mainly in the Ck and BC horizon, occasionally in some of the Bm horizons, but not in the Ah horizons (Table 2-5). Cation exchange capacity increased with elevation and typically decreased with depth, following the same trend as soil organic C (Table 2-6). Base saturation was consistent at or near 100%, with calcium making up over 50% of the cations and magnesium making up around 25% (Table 2-6). The relatively high exchangeable magnesium in these soils has also been reported in the past studies (Spilsbury and Tisdale, 1944; van Ryswyk et al., 1966) and was postulated to be due to the tertiary volcanic rocks in the area. Potassium constitutes between 5 and 10% of the cations present, while iron, aluminum, manganese and sodium are all <5% of the cations present (Table 2-6). These trends determined in 2019 follow closely those previously described at Lac du Bois Grassland across the same elevation transect (Spilsbury and Tisdale, 1944; Tisdale, 1947; van Ryswyk et al., 1966).

Table 2-5. Soil pH, organic and inorganic C, and C/N ratio of five soil profiles across the 400 to 1000 m elevation gradient at Lac du Bois Grassland in 2019. Total C was used in C/N ratio.

Elevation (m)	Horizon	Depth (cm)	pH (1:1 soil:water)	pH (1:2, soil:$CaCl_2$)	Organic C (%)	Inorganic C (%)	C/N
			Brown Chernozem				
	Ah	0 - 15	7.4	6.9	0.98	0.00	9.9
575	Bmj	15 - 35	8.0	7.5	1.48	0.12	9.3
	Ck	35 - 80+	8.4	7.9	0.30	2.00	4.4
			Dark Brown Chernozem				
	Ah	0 – 23	7.2	6.7	1.40	0.00	10.8
711	Bm	23 - 55	8.1	7.7	1.12	0.88	8.6
	Ck	55 - 90+	8.6	8.0	0.80	1.80	12.1
	Ah	0 – 20	6.9	6.4	2.50	0.00	11.4
790	Bm	20 – 51	7.4	6.9	1.70	0.00	10.0
	Ck	51 - 82+	7.3	7.0	0.98	0.00	9.8
			Black Chernozem				
	Ah	0 - 21	6.6	6.1	5.70	0.00	11.0
	Bm1	21 - 42	6.8	6.2	2.70	0.00	10.4
917	Bm2	42 - 58	7.9	7.4	1.08	0.52	9.0
	BC	58 - 71	8.5	8.1	1.60	2.40	16.0
	Ck	71 - 85+	8.6	8.2	0.50	2.50	8.9
	Ah1	0 - 13	6.1	5.6	4.50	0.00	11.5
980	Ah2	13 - 25	6.7	6.0	2.20	0.00	10.0
	Bm	25 - 74	7.2	6.7	0.85	0.00	9.2
	Ck	74 - 92+	8.4	7.9	0.00	1.10	0.0

Table 2-6. Soil horizon depth, cation exchange capacity, exchangeable cations and base saturation of five soil profiles for three chernozemic great groups at Lac du Bois Grassland in 2019.

Elevation	Horizon	Depth	C.E.C	Exchangeable cations							Organic P	Available P	Base Saturation
				Al	Ca	Fe	K	Mg	Mn	Na			
		(cm)	(cmol / kg)	(cmol / kg)	(cmol / kg)	(cmol / kg)	(cmol / kg)	(cmol / kg)	(cmol / kg)	(cmol / kg)	(mg/kg)	(mg/kg)	(%)
Brown Chernozem													
575	Ah	0 - 15	16	0.013	11	0.002	0.84	3.8	0.0052	0.057	130	< DL*	98
	Bmj	15 - 35	22	0.016	16	0.0017	0.51	5	0.0033	0.091	66	< DL	98
	Ck	35 - 80+	15	0.02	8.1	0.002	0.61	5.7	0.0031	0.09	78	< DL	97
Dark Brown Chernozem													
711	Ah	0 - 22.5	19	0.013	12	0.0017	1.1	5.1	0.0076	0.074	490	5.2	96
	Bm	22.5 - 55	17	0.012	9.4	0.0014	0.72	6.6	0.0033	0.074	210	< DL	99
	Ck	55 - 90+	12	0.016	5.7	0.002	0.46	5.7	0.0033	0.066	220	< DL	99
790	Ah	0 - 19.5	25	0.023	15	0.0033	2.2	7.4	0.012	0.07	300	31	99
	Bm	19.5 - 50.5	21	0.017	9.4	0.0018	2.2	9.6	0.0061	0.094	320	26	101
	Ck	50.5 - 82+	21	0.019	5.4	0.0025	2.2	13	0.0078	0.25	180	15	99
Black Chernozem													
917	Ah	0 - 21	33	0.02	25	0.0021	1.7	6	0.016	0.056	910	22	99
	Bm1	21 - 42	21	0.04	15	0.011	1.1	4.9	0.0078	0.07	580	< DL	100
	Bm2	42 - 58	17	0.011	13	0.0025	0.69	3.7	0.0042	0.062	250	6	103
	BC	58 - 71	14	0.02	8.8	0.0024	0.29	4.7	0.0033	0.078	180	< DL	99
	Ck	71 - 85+	13	0.012	6.2	0.0016	0.21	6.4	0.0032	0.11	39	< DL	99
980	Ah1	0 - 13	24	0.018	18	0.002	0.84	4.9	0.047	0.059	720	19	99
	Ah2	13 - 24.5	19	0.019	14	0.0019	0.94	4.1	0.017	0.056	480	7.9	101
	Bm	24.5 - 74	14	0.014	9.1	0.0025	0.89	4	0.013	0.059	250	< DL	100
	Ck	74 - 92+	12	0.014	5.7	0.002	0.22	6.3	0.0032	0.066	120	< DL	102

*<DL means the value obtained was below detections limit for that specific measurement

Soil texture of the surface layer (0-15 cm) across the elevation gradient was loam (12-18% clay, 37-49% silt, 32-51% sand), apart from soils below 500 m in elevation, which were silty loams (22% clay, 53% silt, 24% sand) (Table 2-7). Soil texture from the 15-30 cm depth has been classified as sandy loams (15-21% clay, 37-49% silt, 32-51% sand), with somewhat higher sand content observed at the higher elevations (Table 2-7).

Table 2-7. Soil particle size distribution and textural class for various depths across the elevation gradient at Lac du Bois Grassland.

Elevation	Depth (cm)	Clay (%)	Silt (%)	Sand (%)	Textural class
400 m	0-15	22	53	24	silt loam
400 m	15-30	21	48	31	loam
500 m	0-15	12	37	51	loam
500 m	15-30	15	30	55	sandy loam
600 m	0-15	18	49	32	loam
600 m	15-30	16	46	37	loam
700 m	0-15	16	43	40	loam
700 m	15-30	17	44	39	loam
790m	0-20	19	47	33	loam
790 m	20-51	21	43	36	loam
980 m	0-10	9	46	45	loam
980 m	10-20	10	46	44	loam
980 m	20-30	11	42	47	loam

Soils at Lac du Bois Grassland are classified as Chernozemic soils and they show obvious transition between the Brown, Dark Brown and Black Chernozemic great groups across the elevation gradient. Currently, the Brown Chernozems occur at elevations below about 650 m, where they transition to a Dark Brown Chernozem, which then transition to Black Chernozems around 800 m in elevation (Table 2-8). This is highly dependent on topography and these results are typical for the southern aspect of the grassland.

Table 2-8. Soil colour for selected sites in the Brown, Dark Brown and Black Chernozems at 0-5 cm, 5-15 cm and 15-30 cm depths. Sites were selected on both sides of the boundaries of each great group. Munsell Colour System was used to determine the colour value and chroma on dry samples.

		Depth (cm)		
Great Group	Elevation	0-5	5-15	15-30
Brown Chernozems	400 m	2.5Y 4/4	2.5Y 5/4	2.5Y 5/4
	650 m	2.5Y 5/3	2.5Y 5/3	2.5Y 5/4
Dark Brown Chernozems	675 m	2.5Y 4/3	2.5Y 4/3	2.5Y 4/4
	800 m	2.5Y 4/3	2.5Y 4/3	2.5Y 4/3
Black Chernozems	825 m	2.5Y 3/2	2.5Y 3/2	2.5Y 3/3
	1000 m	10YR 3/2	10YR 3/3	10YR 4/3

Across the elevation gradient, soil C concentration ranged from 0.82% to 13.5% at the 0-5 cm depth, from 0.84% to 4.95% at the 5-15 cm, and 0.89% to 3.5% at the 15-30 cm depth (Table 2-9). Soil C concentration with depth seems to be more varied in the upper grassland, but in the lower and middle grassland, only a maximum of about 1% C concentration difference was seen between 0-5 cm depth and 15-30 cm depth (Table 2-9, Appendix A). The increase in soil C observed across the elevation gradient from drier to more mesic areas of the grassland is also to be expected and has been well documented across many similar transects in a variety of grassland types (Hewins et al., 2018). Carbon stock increased across the elevation gradient from 2.87 kg m-2 to 8.52 kgm-2 from the 0-30 cm depth (Fig. 2-4). Soil C stock (Fig. 2-4) showed a polynomial curve across the elevation gradient, with a slight decrease from 400 m to 500 m in elevation, and then increasing with elevation, similar to SOC (Fig. 2-3).

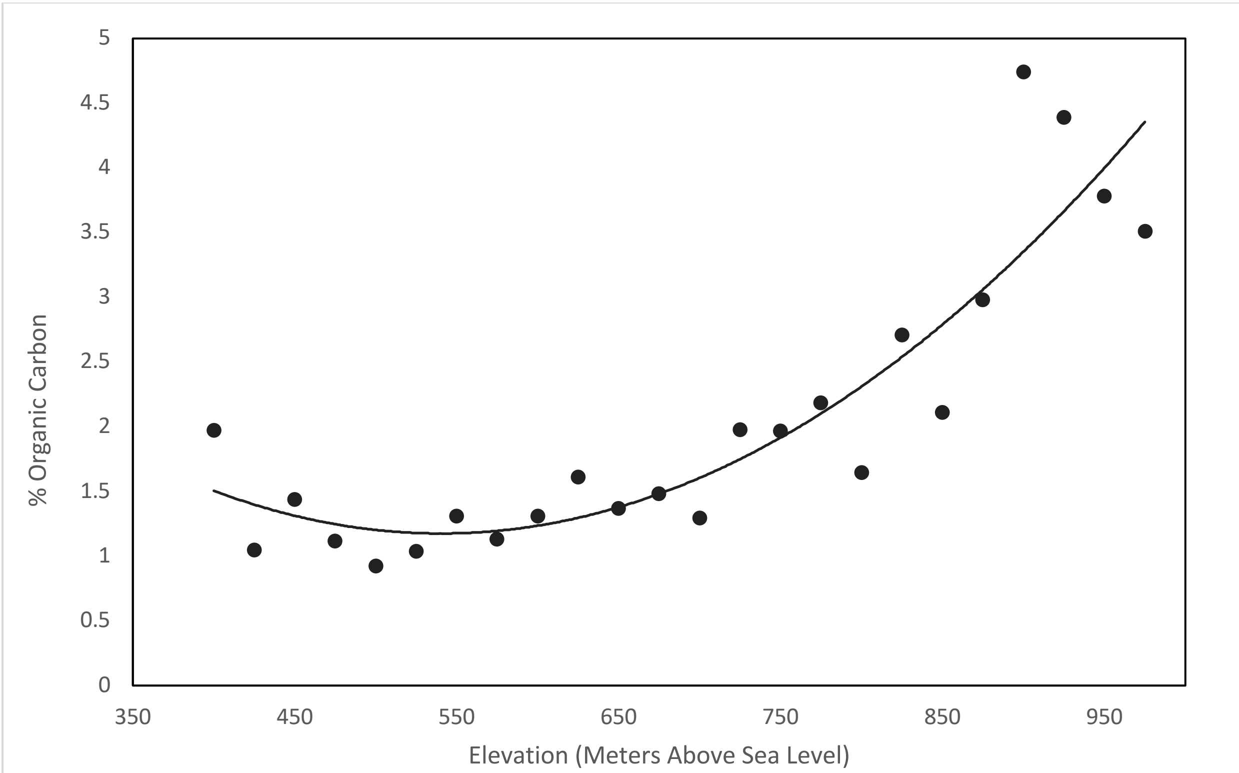

Figure 2-3. Weighted average of soil organic carbon (%) across an elevation gradient ranging from 400 to 1000 m above sea level at Lac du Bois Grassland in 2019.

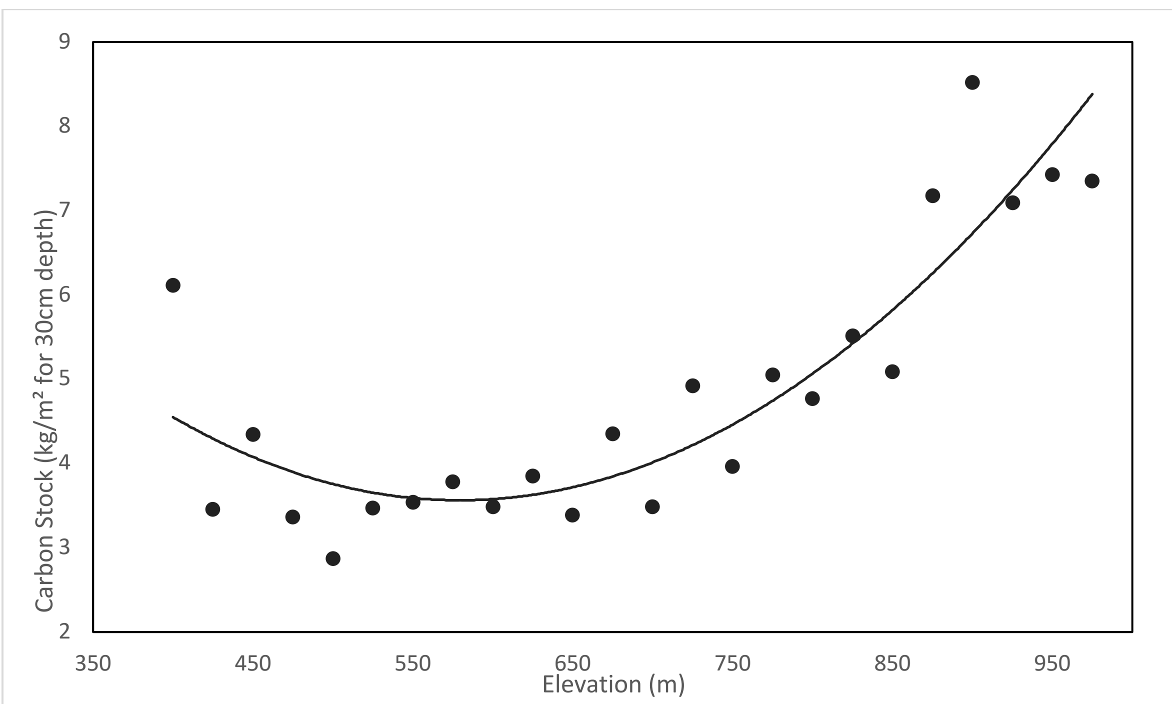

Figure 2-4. Carbon stock for the 0-30 cm depth across the 400 to 1000 m elevation gradient at Lac du Bois Grassland in 2019.

Soil C concentration in the Brown Chernozems ranged from 0.8% to 2.8% at the 0-5 cm depth, 0.8% to 1.6% at the 5-15 cm depth and 0.9% to 2.1% at 15-30 cm depth (Table 2-9). Across this portion of the elevation gradient, SOC from 0-5 cm was 2.3% at 400 m (a.s.l.), then 0.8% at 525 m (a.s.l.), and 2.8% at 625 m (a.s.l.) before the area transitioned into the Dark Brown Chernozem (Table 2-9). The greater SOC observed at 400 m asl with the Brown Chernozem was most likely due to the presence of finer textured soils with high proportion of silt (Table 2-7), which might have contributed to greater C stabilization (Burke et al., 1989; Buschiazzo et al., 1991; Baldock and Skjemstad, 2000). These lowest parts of the Lac du Bois Grassland used to be a glacial lake (Watson, 1977) and the fine textured deposits from that lake have been redistributed by wind across the valley, with the most deposition occurring at lower elevations of the Lac du Bois Grassland (Watson, 1977). Once above the 500 m in elevation, the texture changes to a loam (at 0-15 cm depth) and a sandy loam (at the 15-30 cm depth) (Table 2-7). In addition, this zone of the grassland receives very limited growing season precipitation (96 mm from April to October) and much of its moisture comes from snow melt. Because of this, even slight variations in soil texture can lead to variation in soil C (Craine et al., 2010; Li et al., 2008), and may have led to lower SOC observed above 500 m asl relative to areas at 400 m asl.

In the Dark Brown Chernozems (650 to 825 m a.s.l.), C concentration ranged from 2.0% to 3.1% at the 0-5 cm depth, 1.6% to 2.4% at the 5-15 cm depth and 0.9% to 1.8% at 15-30 cm depth (Table 2-9). This area can be difficult to distinguish from the Brown Chernozemic zone due to SOC values only being slightly higher in the Dark Brown Chernozemic zone, but the soil colour was still different enough allowing differentiation of these two great groups (Table 2-8).

The Black Chernozems had C concentrations that ranged from 2.8% to 13.5% at the 0-5 cm depth, 2.2% to 5.0% at the 5-15 cm depth, and 1.9% to 3.0% at the 15-30 cm depth (Table 2-

9). The wide range of soil C concentrations observed at the 0-5 cm depth was due to one site that had 10.0% and 17.0% C. This site was under grassland vegetation, but it was also surrounded by forest, which may have affected the observed high C concentration values. Without this site the C concentration at 0-5 cm depth ranged from 2.80% to 8.1%. The Black Chernozems range from 825 to 1,000 m a.s.l. where the boundary between open grassland and the Interior Douglas-fir Forest has been shifting for thousands of years (Pettapiece, 1969; Brayshaw, 1970). The soils in this zone are very distinct from the zones dominated by the other two Chernozemic great groups. *Festuca campestris* dominates the landscape, producing large amount of underground biomass comprised of fine roots and more root exudates (Kuzyakov and Domanski, 2000). Together with the higher P/E in this area, this leads to formation of a distinct Ah horizon that is much darker and richer in SOC than the underlying horizons. The vegetation community in this zone is the most productive, with almost no bare soil or cryptogamic crust (Table 2-3). The transition between zones with the Brown and Dark Brown Chernozems was gradual, while the transition between zones with Dark Brown and Black Chernozems was very noticeable both in terms of plant species composition, aboveground biomass, and soil properties.

At Lac du Bois Grassland, SIC was a sizeable part of total soil C particularly at the lower depths. As expected, SIC was hardly present at the 0-30 cm depth of the upper grassland as well as the 0-15 cm depth of the lower and middle grasslands (Table 2-9). However, total soil C cannot be assumed to equal SOC below 15 cm in the lower and middle grasslands as SIC is present in substantial amounts there. This shows the importance of considering SIC when calculating soil organic C stocks of semiarid ecosystems especially those with Ck horizons as SIC can alter the calculations greatly.

Table 2-9. Soil organic carbon, inorganic carbon, polysaccharides and permanganate oxidizable carbon across the elevation gradient at Lac du Bois.

Great Group	Elevation (m a.s.l.)	Soil Organic Carbon (%) 0-5 cm	5-15 cm	15-30 cm	Soil Inorganic Carbon (%) 0-5 cm	5-15 cm	15-30 cm	Polysaccharides (%) 0-5 cm	5-15 cm	15-30 cm	POXC (mg/kg) 0-5 cm	5-15 cm	15-30 cm
Brown Chernozems	400	2.34	1.55	2.13	0.07	0.15	0.22	0.99	0.76	0.87	496.3	229.6	161.3
	425	1.40	0.90	1.04	0.00	0.00	0.00	1.10	1.04	1.09	489.0	277.4	352.0
	450	2.15	1.40	1.22	0.00	0.00	0.03	0.91	0.65	0.79	676.9	372.4	320.7
	475	1.48	0.84	1.18	0.00	0.03	0.60	1.28	0.75	0.94	471.2	196.5	190.4
	500	1.15	0.86	0.89	0.00	0.04	0.14	0.79	0.96	0.72	335.7	314.9	260.0
	525	0.82	1.15	1.04	0.00	0.00	0.11	0.75	0.56	0.75	358.7	330.1	321.1
	550	1.10	1.55	1.22	0.00	0.05	0.89	1.05	0.79	0.85	257.6	350.8	276.1
	575	1.18	1.08	1.15	0.00	0.00	0.00	1.00	1.38	1.24	424.8	226.3	246.6
	600	1.50	1.45	1.15	0.00	0.00	0.00	0.89	0.88	1.06	456.7	391.1	256.4
	625	2.78	1.41	1.36	0.00	0.04	0.10	0.97	0.87	0.81	803.0	423.2	323.7
Dark Brown Chernozems	650	2.00	1.40	1.14	0.00	0.00	0.17	0.71	0.76	0.76	580.3	337.4	233.9
	675	2.21	1.70	1.10	0.14	0.00	0.00	0.93	0.86	0.75	724.1	459.4	251.1
	700	1.95	1.55	0.90	0.00	0.00	0.03	0.54	0.90	0.67	623.5	385.9	252.3
	725	2.85	1.95	1.70	0.00	0.00	0.00	0.97	0.58	0.70	793.7	406.8	364.0
	750	2.45	2.35	1.55	0.00	0.00	0.00	1.38	0.96	0.58	684.2	553.0	212.2
	775	3.10	2.25	1.84	0.00	0.00	0.46	1.20	0.87	0.69	854.8	545.1	332.0
	800	2.10	2.10	1.20	0.00	0.00	0.00	0.71	0.92	0.90	658.5	492.1	182.5
Black Chernozems	825	3.55	2.85	2.34	0.00	0.00	0.06	1.28	0.56	0.70	720.7	750.6	489.5
	850	2.80	2.15	1.85	0.00	0.00	0.00	1.58	1.17	0.52	821.4	511.2	386.9
	875	4.20	3.10	2.50	0.00	0.00	0.00	1.09	0.74	0.66	1120.8	768.2	587.5
	900	8.05	4.95	3.50	0.00	0.00	0.00	2.14	1.63	1.23	1367.9	1065.9	706.6
	925	13.50	3.50	1.95	0.00	0.00	0.00	4.24	1.38	0.71	1427.8	1052.0	715.2
	950	5.40	4.90	2.50	0.00	0.00	0.00	2.43	2.33	1.67	1188.9	1002.7	518.3
	975	4.90	3.47	3.08	0.00	0.03	0.08	2.14	2.06	1.82	1189.7	985.5	692.3

Polysaccharides and POXC are two soil organic C pools which represent more active C, which is more responsive to management changes than total organic C (Evans et al., 2012). Although we do not have historic values for these soil C pools, documenting them now will allow future comparison based on grassland management changes and recovery.

Polysaccharides, as described by DAEP, make up a large proportion (i.e., 1/3 to ½) of SOC at the 0-5 cm depth and this trend continued down to 30 cm (Table 2-9 and Appendix B). Polysaccharides are a soil C fraction formed from microbial activity, plant root exudates and fine root material and have been shown to aid in aggregation in soil (Cheshire et al., 1973; Tisdall and Oades, 1982; Kiem and Kögel-Knabner, 2003). A high proportion of polysaccharides in grassland ecosystems is to be expected due to the high amount of fine root material from bunchgrasses. Other studies carried out on the Lac du Bois Grassland have also reported similarly high proportions of soil polysaccharides within SOC (Evans et al., 2012).

POXC has become a popular soil C index recently due to its rapid and inexpensive measurement. It is also considered more useful in measuring short-term changes in SOC than monitoring total organic C due to its rapid turnover rate in the soil (DuPont et al., 2010; Lucas and Weil, 2012; Margenot et al., 2015). POXC makes up a much smaller proportion of total organic C than polysaccharides, accounting for ~1-2% of SOC at Lac du Bois. Despite being a very small proportion of SOC, it follows a similar trend as both SOC and polysaccharides over the elevation gradient. This is to be expected as the strong correlation between these three organic C pools has been shown before (Weil et al., 2003; Calderón et al., 2017; Lussier et al., 2020)

2.3.2. Reassessment of the Boundaries of the Chernozemic Great Groups across Elevation Gradient at the Lac du Bois Grassland

Because I used the same topographic criteria for the site selection process as van Ryswyk et al. (1966) and also stratified my sampling by elevation bands so that I sampled every 25 m in elevation gain, it was possible to evaluate the effect of elevation on measured soil properties, while reducing potential variability among sampling sites that would be caused by differences in slope, aspect, and curvature. In addition, I located weather stations as close as possible to the original locations based on the reported elevations of the stations used in the study by van Ryswyk et al. (1966) with the goal to evaluate how present weather variables influence soil properties and plant composition. In general, I tried to stay as close as possible to the original sampling locations of the study by van Ryswyk et al. (1966) and to use similar soil analytical methods. This was not always possible for several reasons. First, there were no exact site locations for the 1961 study, and I had to use anecdotal information for best approximations. Second, the lower grassland from the 1961 study has been paved over in early 2000s when it was incorporated into the Batchelor Hill suburb within the city of Kamloops. Another substantial difference between my study and the 1961 study by van Ryswyk et al. (1966) was in the use of LiDAR derived digital elevation model (DEM) and new laboratory methods and equipment, which were not available in 1961. These limitations prevented a direct comparison between 1961 and 2019 data, but I was still able to use 2019 topographic, microclimate and soil variables to re-evaluate the boundaries among Chernozemic great groups and associated plant communities and soil C storage.

Weather variables, averaged for 1959-1961 and 2017-2019 growing season (April – October), are shown in Table 2-10. Monthly mean, mean minimum and mean maximum air

Table 2-10. Three-year averages for April-October during 1959-1961 and 2017-2019 of the monthly mean maximum, mean minimum, mean temperature, precipitation and precipitation effectiveness across the 400 to 1000 m elevation gradient at Lac du Bois Grassland. Data from 1959-1961 was sourced from van Ryswyk et al. (1966).

	April - October	
	1959-1961	2017-2019
Chernozemic Great Group (elevation, m)		
	Monthly mean max. temperature (°C)	
Brown (353/ - m)	22.5	-
Brown (520/575 m)	21.2	21.8
Dark Brown (695/711 m)	19.7	21.3
Dark Brown (- /790 m)	-	20.2
Black (890/917 m)	18.2	17.8
Black (950/980 m)	17.4	18.0
	Monthly mean min. temperature (°C)	
Brown (353/ - m)	9.3	-
Brown (520/575 m)	10.7	8.7
Dark Brown (695/711 m)	8.6	7.2
Dark Brown (- /790 m)	-	7.5
Black (890/917 m)	7.3	5.8
Black (950/980 m)	5.9	7.6
	Monthly mean temperature (°C)	
Brown (353/ - m)	15.5	-
Brown (520/575 m)	16.1	15.1
Dark Brown (695/711 m)	14.3	13.8
Dark Brown (- /790 m)	-	13.7
Black (890/917 m)	13.0	11.7
Black (950/980 m)	11.5	12.5
	Precipitation (cm)	
Brown (353/ - m)	13.55	-
Brown (520/575 m)	13.36	10.03
Dark Brown (695/711 m)	14.96	21.57
Dark Brown (- /790 m)	-	21.43
Black (890/917 m)	18.00	27.75
Black (950/980 m)	18.80	29.52
	Precipitation effectiveness (P/E) ratio	
Brown (353/ - m)	1.11	-
Brown (520/575 m)	1.08	0.85
Dark Brown (695/711 m)	1.29	2.19
Dark Brown (- /790 m)	-	2.19
Black (890/917 m)	1.71	3.12
Black (950/980 m)	1.93	3.14

NOTE: The numbers in the brackets correspond to the elevation of the weather stations with the 1st number relating to the 1961 position and the second being the 2019 position. "-" indicates that no weather station is present at that elevation; hence, no data were collected.

temperatures for April to October were similar across Lac du Bois Grassland in both 1959-1961 and 2017-2019 (Table 2-10). Average 2017-2019 April to October precipitation and precipitation effectiveness were higher than in 1959-1961 at all elevations, except the lowest elevation site (Table 2-10). The initial two decades of the 21st century have seen more extreme weather than any other time period in recorded history due to climate change (Coumou and Rahmstorf, 2012). Lac du Bois and the BC Southern Cordillera region are not exempt from this, with 2017 being the hottest and driest year in this region since 1961 (Kirchmeier-Young, 2019). Further monitoring of weather parameters along the elevation gradient is needed to be able to more accurately assess impacts of land use management on plant communities and soil C storage under changing climate.

There have also been substantial changes in plant species composition in the middle and upper grassland areas between 1961 and 2019 (Fig. 2-2). In 1961, the vegetation community was classified into three distinct groups, which were said to have distinct boundaries. In 2019, the differences between the vegetation communities in the lower and middle grassland, which used to be quite distinct, have become less evident if present at all. The two large changes that caused this are the expansion of *Artemisia tridentata* into the middle grassland, and the decrease of *Hesperostipa comata* in the middle grassland (Fig. 2-2). *Artemisia tridentata*, which in 1961 was only present in the lower grassland up to 640 m in elevation (van Ryswyk et al., 1966), is now present up to 790 m in elevation. This species has become fairly dominant in the middle grassland, an area where it used to be very sparse in 1961 if present at all.

Debate surrounding an acceptable density and extent of *Artemisia tridentata* across grassland ecosystems in BC has continued to be focused on whether the introduction of livestock or active fire suppression on the landscape has caused the present-day shrub density. Cawker

(1982) argues that there is substantial evidence through pollen records taken from multiple locations in grassland areas of southern BC that *Artemisia tridentata* has been present on the landscape for thousands of years. Indeed, livestock management and fire suppression have a significant influence on shrub establishment and eradication as bare soil is needed for germination and fire will kill the plant without re-sprouting. *Hesperostipa comata* has decreased significantly across the grassland relative to 1961, when it dominated the middle grassland. *Pseudoroegneria spicata* is now abundant across the lower and middle grassland, achieving 94 – 100% frequency at the Daubenmire plant community transects (Table 2-2), which is indicative of improved grassland health with a shift from low-seral towards late-seral species. This leaves a lower and middle grassland dominated by *Pseudoroegneria spicata, Artemisia tridentata* and *Poa secunda*. The Black Chernozemic upper grassland zone has also experienced changes in plant species composition over the last 58 years. The upper grassland is now primarily *Festuca campestis*, with 98% frequency at the Daubenmire plant community transects (Table 2-2), instead of *Poa pratensis, Poa secunda* and *Pseudoroegneria spicata* as it was recorded in 1961 (van Ryswyk et al., 1966). This is also indicative of a shift from low-seral towards late-seral species. However, there are still sporadic areas with higher grazing intensity and similar diversity to 1961 in some areas of the upper grassland.

In 1961, the middle *Hesperostipa-Poa* zone was less productive than the *Artemisia* zone at lower elevation, despite the more favourable microclimate (van Ryswyk et al., 1966), possibly due to a livestock preference of the middle grassland over the lower grassland due to access to water and/or topography. This vegetation also did not match the typical plant species composition for grasslands in this elevation (Tisdale, 1947). In 2019, the vegetation community for the middle grassland was representative of the potential natural community (PNC) and desired species in the area for the ecological position it holds (Tisdale, 1947). Overall, the dominance of late-seral bunchgrass species across all elevations of the Lac du Bois Grassland represents substantial recovery from their degraded state as documented by van Ryswyk et al. (1966).

Despite these changes in plant community, soil C stock observed across the elevation gradient in 2019 at the Lac du Bois Grassland has not increased in the past 58 years (Fig. 2-5). In 1961, van Ryswyk et al. (1966) reported C stock in $g/2dm^3$. I replicated this unusual unit (Fig. 2-5), assuming it meant the soil C stock in g/dm^2 at the 0-2 dm depth. Soil C stock levels from 1961 and 2019 are similar in the lower grassland, but the differences can be seen particularly in the middle and upper grassland (Fig. 2-5). These are a few possible explanations for these differences. First, although we used the same topographic criteria to select sample locations along the elevation gradient, van Ryswyk did not have the luxury of a LiDAR derived digital elevation model and sophisticated software packages to accurately identify locations that satisfied our topographic criteria. Second, there are possible discrepancies between C stock calculations with respect to corrections for coarse fragments in our two studies. In the lower grassland, where soil C stock was similar between 1961 and 2019, there is a lower coarse fragments content due to presence of the thick aeolian veneer. This could explain why C stock values were similar, as the coarse fragment content correction would have a smaller effect. However, the upper grassland, with greater difference in soil C stock between 1961 and 2019, is characterized by a greater content of coarse fragments and it has also been more eroded over the decades of heavy grazing. This shows the importance of correcting for coarse fragments in calculations of the soil C stock, and just how substantial the differences can be among different studies if no correction is done. Finally, it is possible the soil organic C stock did in fact decrease since the original study in 1961 despite the recovery and productivity of the present grassland community.

Regardless of which of these reasons best explains observed differences in the soil C stock along the elevation gradient after 58 years, there is tremendous value in documenting the present inventory of soil organic C from the 0 to 30 cm depth with the proper correction for coarse fragments. Another soil parameter that deserves more careful attention, especially on grassland soils high in carbonates, is the determination of SIC, since omitting SIC could also lead to overestimations of soil C stock.

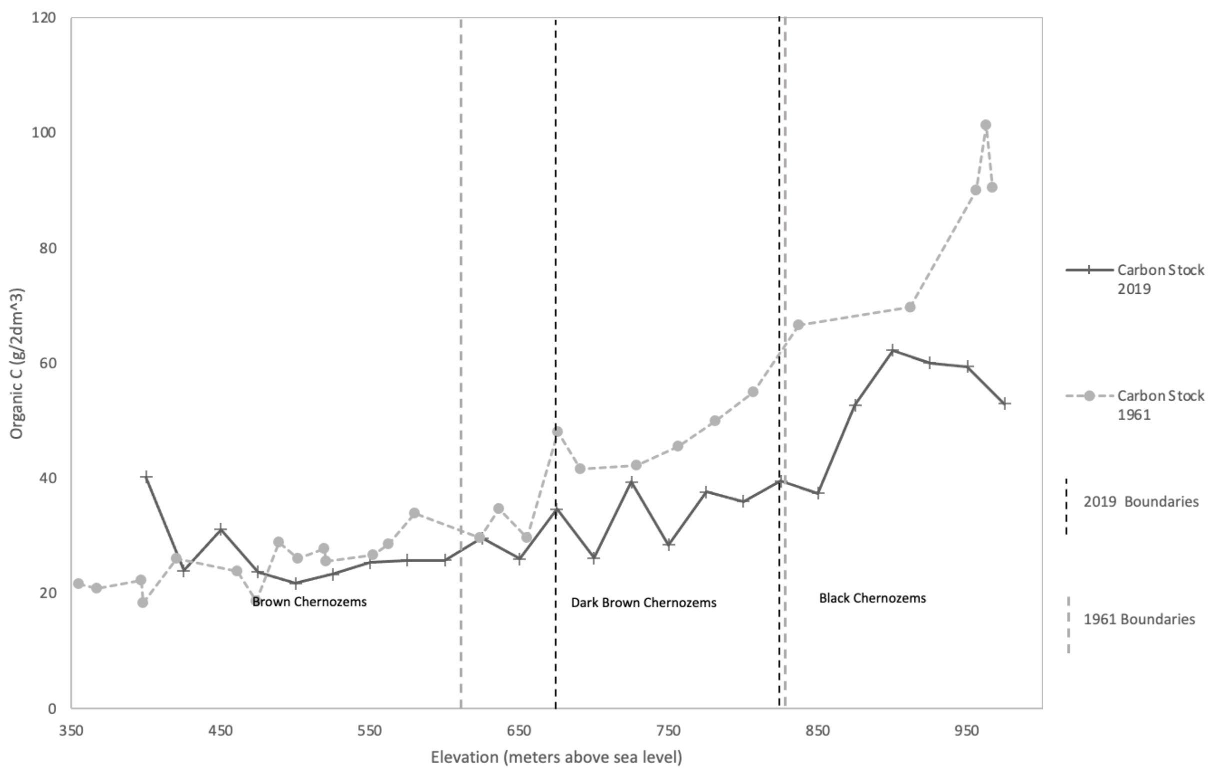

Figure 2-5. Soil organic carbon at the 0-20 cm depth across the 400 to 1000 m elevation gradient at the Lac du Bois Grassland in 1961 (grey circles) and 2019 (black crosses). Data from 1959-1961 was sourced from van Ryswyk et al. (1966).

The boundary between Brown and Dark Brown Chernozems, as observed in 2019, is 60 m higher in elevation than it was reported in 1961. It is possible that due to the climate change and changes in plant community, with the middle grassland becoming an extension of the lower grassland, the lower grassland is creeping up this elevation gradient. The moving of biogeoclimactic zones due to climate change has been predicted by several studies carried out in BC (Hamann and Wang, 2006; Wang et al., 2012), and this might have been also occurring at the Lac du Bois. Future research using the same locations sampled in 2019 will be able to determine if the boundaries of Chernozemic great groups are indeed changing, or if this was simply due to differences in sampling locations between the two studies.

With presence of the more typical vegetation communities across the elevation gradient and better grazing management, Lac du Bois Grassland will continue to recover from the past degradation and provide a stable ecosystem for flora and fauna in years to come. Although soil C stock has not increased compared to 1961, with a healthier plant species composition and better grazing management, increased soil C will inevitably follow if these soils are not already displaying steady state condition for soil C storage.

2.5 Conclusions

Results from this study show there have been substantial changes in plant species composition in the middle and upper grassland at Lac du Bois Grassland over the 58 years since van Ryswyk et al. (1966) described it. *Pseudoroegneria spicata* and *Festuca campestris* are presently the dominant bunchgrass species in the middle and upper grassland, respectively, even thought they were completely absent or present as minor components of these plant communities at the time of heavy degradation as described in 1961. Presence of these late-seral bunchgrass species in 2019 in these zones is indicative of substantial recovery from their degraded state as documented in the study by van Ryswyk et al. (1966). The recovery has been a result of the improved range management practices that started in mid-1970s. At the same time, *Artemisia tridentata* has notably increased in the middle grassland, a sign of high grazing pressure, eliminating the previously observed differences in the plant species communities between the lower and middle grasslands. The lower grassland remained relatively unchanged over 58 years, likely due to lower historical grazing pressure caused by presence of steep hillsides and limited access to water for cattle.

Despite these changes in plant community, soil C stock has not increased, and may have even decreased across the grassland in the past 58 years. This has been particularly represented in the middle and upper grasslands, with the lower grassland having similar soil C stock compared to 1961. There is tremendous value in documenting the soil organic C throughout the whole soil profile instead of just focusing on the top layers and in correcting soil C stock calculations for coarse fragments and SIC. The lack of the coarse fragment corrections in the study by van Ryswyk et al. (1966) was the most likely reason that led to discrepancies in soil C stock observed at upper grasslands between 1961 and 2019. Correcting for coarse fragment content at Lac du Bois for the data collected in 2019 had a substantial effect on soil C stock, decreasing C stock values to 36% of the original value before correction (88% average). SIC was shown to be present in substantial amounts in the lower and middle grassland below the 15 cm depth at Lac du Bois Grassland, constituting up to 42% of total soil C.

The boundary between the Brown and Dark Brown Chernozems increased in elevation by ~60 m. This can possibly be attributed to difference in sample location but could also be a product of environmental, microclimate and plant community change. The increase in precipitation, decrease in air temperature, and therefore increased P/E with increasing elevation across the Chernozemic great groups sequence were once again the most evident drivers of the differentiation of Chernozemic great groups at the Lac du Bois Grassland. Specifically, P/E was the variable that had the strongest impact on Chernozemic great group distribution.

Lac du Bois Grassland, with its long history of studies focused on plant species composition and soil properties, serves as a unique study area that will continue to be of interest for future studies. Detailed descriptions of plant species composition and soil properties dating back to 1940s, 1960s all the way to the present day are providing solid baseline data for future studies as well as more accurate modeling of soil C sequestration and climate change in arid and semi-arid grassland ecosystems.

Chapter 3: General Conclusion and Recommendations for Future Studies

3.1 General Conclusions

Fifty-eight years after van Ryswyk et al. (1966) described microclimate, soil, and vegetation at Lac du Bois Grassland, there was a need for an updated description of this unique ecosystem. Of those 58 years, last 44 years have been under seasonally deferred moderate cattle grazing, allowing for noticeable recovery of plant species composition. The lower grassland's plant species composition has remained fairly similar to 1961, still being dominated by *Pseudoroegneria spicata* and *Artemisia tridentata*. This is likely due to this zone of the grassland having a lower grazing pressure due to it being steeper, having a more arid microclimate and generally lower aboveground biomass production. The middle and upper grassland's plant species composition has changed substantially over the 58 years. The middle grassland, once dominated by the *Hesperostipa comata*, is now a continuation of the lower grassland, being dominated by *Pseudoroegneria spicata* and *Artemisia tridentata*. Although similar in species composition, this grassland zone has significantly decreased bare soil and increased above ground biomass production. This change is the sign of transition between an early and late seral stage community due to improved grassland management in the middle grassland at Lac du Bois. Similarly, the upper grassland has shifted to a late seral stage community. In 1961, this area was dominated by *Artemisia tridentata, Pseudoroegneria spicata* and *Poa secunda*, but now is completely dominated by *Festuca campestris*. These changes in the plant species composition at Lac du Bois are important sign of recovery at this grassland, indicating the positive effects of improved rangeland management.

Despite these positive changes in plant species composition, organic C stock has not increased across the grassland since 1961. This is not what was expected based on the recovery and shift to late seral stage communities seen across the grassland. Other studies have shown that C cycling and decomposition slow down under a shift from exotic to native vegetation as well as shifts to late seral communities on grassland ecosystems (Odum, 1969; Yahdjian et al., 2017; Knops and Tilman, 2000). The lower grassland showed similar soil C stock values to 1961 data, but the middle and upper grassland have shown marked decreases in soil C stock. This could potentially be due to a discrepancy in corrections from coarse fragment content or SIC. The SIC was found primarily below the 15 cm depth in the lower and middle grassland, while soil layers above 15 cm depth or at any soil layers in the upper grassland did not have any noteworthy amounts of SIC. Despite SIC being limited to the soils below 15 cm in depth in the lower and middle grassland, it constituted up to a maximum of 42% total soil C in this area. This demonstrates just how important measurement of SIC in semiarid ecosystems can be for determination of the soil C stock. Similarly, coarse fragment content at Lac du Bois Grassland had a substantial impact on soil C stock. In this study, correcting for coarse fragment content decreased the calculated soil C stock at Lac du Bois to 36% of the original value before correction (88% average). Both variables had a tremendous impact on soil C storage calculations and need to be considered when thinking of management implications for soil C storage across many ecosystems.

LiDAR derived topographic variables were also able to predict soil C stock across the southern aspect of Lac du Bois Grassland. The stratified sampling regime attempted to minimize the variation in many of these topographic variables, allowing elevation effects on organic C stock to be determined, yet relationships were still present between these topographic variables and soil C stock. The distance to ground water (Channel Network Base Level) turned out to be a powerful variable when prediction with only one or two variables, showing the importance of access to moisture in the semiarid grassland.

The importance of access to moisture in this ecosystem can also be seen in P/E. This variable, which takes into account precipitation, temperature and evapotranspiration, remains very powerful in determining the distribution of Chernozemic great groups at Lac du Bois. This is the same conclusion that van Ryswyk et al. (1966) also made. Interestingly, the boundary between the Brown and Dark Brown Chernozems has shifted up ~60m at the Lac du Bois. As the plant species composition across these two grassland zones has become very similar, the possibility of the lower, more arid zones shifting up in elevation is entirely possible. This possibility is furthered by climate change and increasing global temperatures. The boundary between the middle and upper grassland (Dark Brown and Black Chernozems) remains stagnant and unmistakable.

The need to monitor change at Lac du Bois Grassland is more important than ever before. Lac du Bois Grassland has had a long history of research and will continue to be an ecosystem of interest in years to come. Lac du Bois is also an important ecosystem for observing the effects of climate change due to its large differences in temperature and precipitation across its 600 m elevation change. This study can provide a new baseline for monitoring change, allowing for future research at Lac du Bois and other grasslands in the Southern Interior of BC.

3.2 Recommendations for Future Research

This study was an essential step for an up-to-date description of this unique grassland, but much remains to be done. First, presently we have plant community descriptions and soil physical and chemical properties to 30 cm depth, showing a large portion of the soil C stock across the southern aspect of Lac du Bois Grassland. Deep C storage at Lac du Bois remains an unknown for both organic and inorganic C. Sampling to 60 cm depth or deeper would shine a light on deep C storage and help our understanding of SIC storage across the grassland. Along with this, obtaining soil pH and texture data would allow better understanding of the role that organic and inorganic C play in total soil C. Just as this study has created a new baseline description for the southern aspect of Lac du Bois, future descriptions of C storage at deeper depths (i.e., >30 cm) will allow better monitoring of changes due to climate and management.

Second, this study sought only to replicate study by van Ryswyk et al. (1966) by focusing at the southern aspect of the grassland. Although this is the major aspect present at the Lac du Bois Grassland, this ecosystem is extremely undulating and complex. Mapping soil C across all aspects, curvatures, slope lengths and positions, and elevations of Lac du Bois Grassland, not just the southern aspect would be a next step. Increasing the knowledge of soil carbon dynamics across all topographies of Lac du Bois is vital for informed rangeland management decision and grassland protection.

Finally, as I have followed up with van Ryswyk's study from 1961, more regular follow up at Lac du Bois is essential for monitoring changes in soil C dynamics, plant species composition changes and the effects of climate change. With the aid of modern technology, our exact sample sites and weather stations are known, and spatial variation can be removed from future follow up studies. This will make the temporal variation measurable and elucidate how time has affected the soil and plant communities at the Lac du Bois Grassland. Open grasslands, such as Lac du Bois are sensitive ecosystems and will be heavily affected by climate change and land use in years to come. Understanding these ecosystems will allow for the proper management decisions allowing us to protect these important ecosystems and the endangered species in them as well as combat the effects of climate change.

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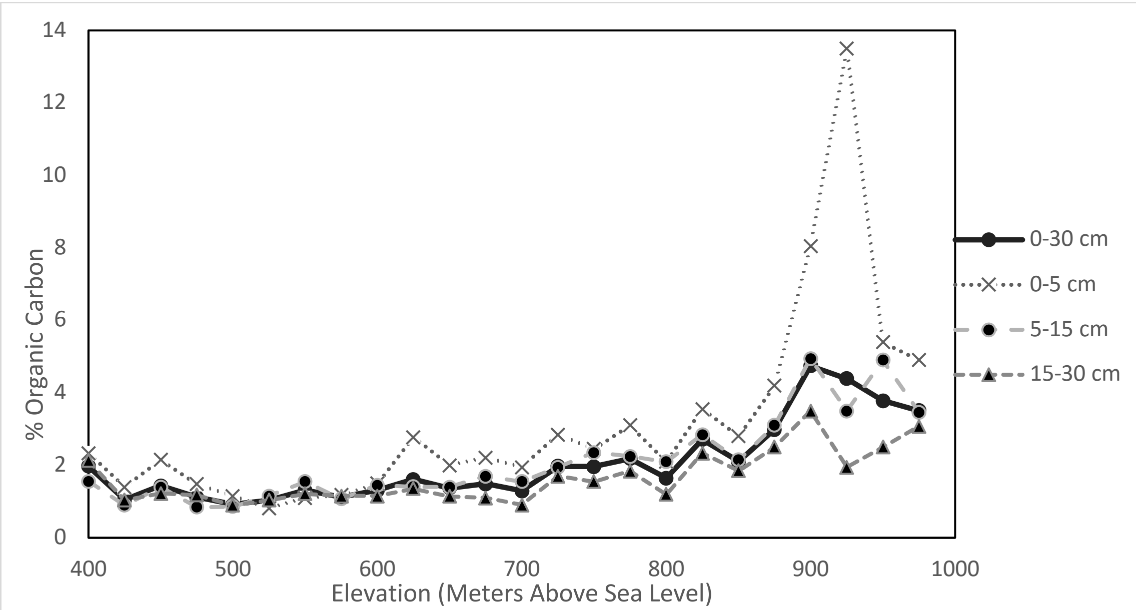
Appendix

Appendix A. Soil organic C at three depths of sampling

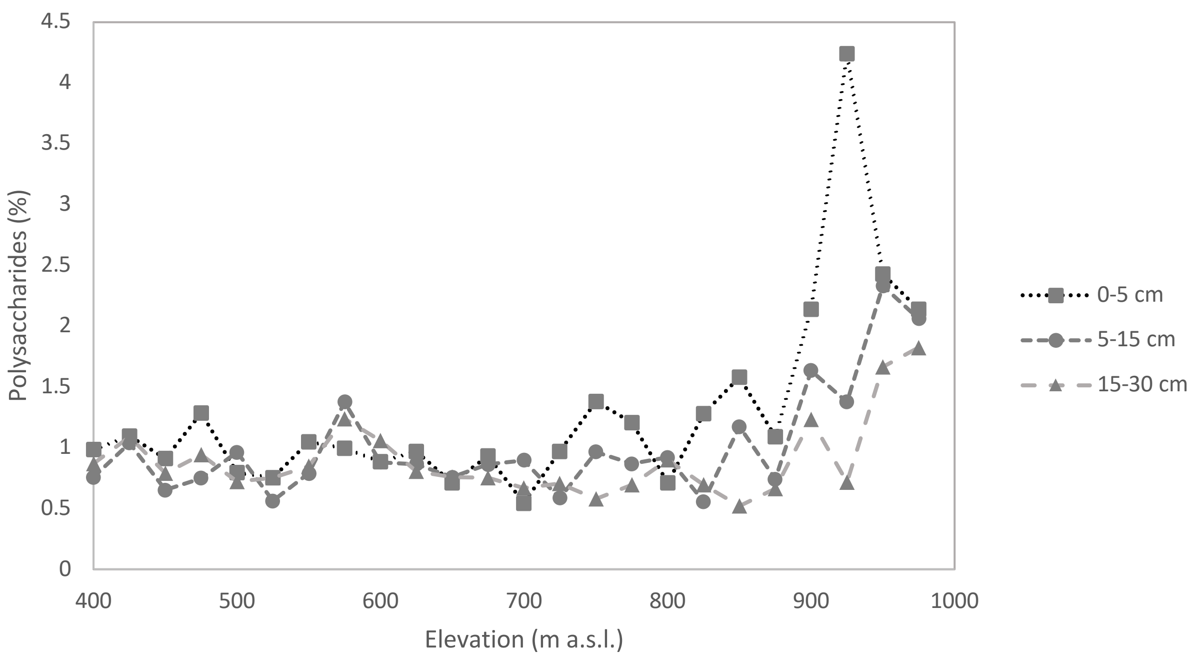


Appendix A-1. Soil organic carbon (%) across an elevation gradient ranging from 400 to 1000 m above sea level at Lac du Bois Grassland in 2019. Dashed lines show soil organic carbon concentrations from the 0-5 cm, 5-15 cm and 15-30 cm depths, while the solid black line shows the average over all sampled depths.

Appendix B. Detailed Description of Soil Analyses

DAEP

Using Erlenmeyer flasks, 0.75 g of soil and 100 mL of 0.5 M H_2SO_4. The flasks were covered with tinfoil and autoclaved for 1 hour at 121 °C and 103 kPa. Samples were then filtered with Whatman 42 filter paper and diluted into a 200 mL volumetric flask. Glucose standards were made to 20 µg/mL, 30 µg/mL, 40 µg/mL, 60 µg/mL, 80 µg/mL, 100 µg/mL, and 120 µg/mL. To each of 1 mL sample solution and 1 mL of each glucose standard, 1 mL of 0.05 g/mL phenol solution and 5mL 18 M H_2SO_4. The 18 M H_2SO_4 was added using a burette to ensure full mixing of the solution. The solutions were then placed in the oven at 30°C for 25 minutes after which 150 µL were pipetted in triplicate onto a 96-well microplate, along with dH_2O blanks and the glucose stock solutions. Plates were run on a microplate TECAN spectrophotometer (TECAN Group Ltd., Zurich, Switzerland) at 490 nm to determine absorbance.



Appendix B-1. Polysaccharides (%) at 0-5, 5-15 and 15-30 cm depth across an elevation gradient at Lac du Bois Grassland in 2019.Chernozemic great groups, determined using the colour criteria laid out by the Soil Classification Working Group (1998).

POXC

Potassium permanganate ($KMnO_4$) stock solution was prepared at 0.2 M and pH 7.2. Standards were made at 0.005 M, 0.01 M, 0.015 M and 0.02M $KMnO_4$ using the 0.2 M standard solution with dH_2O. Samples were prepared using 2.5 ± 0.02 g of soil in a 50 mL centrifuge tube. 2 mL of 0.2 M $KMnO_4$ and 18 mL dH_2O were added to the soil and the tubes were shaken on high (240 oscillations per minute) for exactly 2 minutes. Samples were then placed in a dark room for 10 minutes to settle and react, after which 0.5 mL of the supernatant was taken and added to 49.5 mL dH_2O. This mixture was inverted to mix and 250 µL was added in triplicate onto a 96-well microplate, along with dH_2O blanks and the four $KMnO_4$ stock solutions. Plates were run on a microplate TECAN spectrophotometer (TECAN Group Ltd., Zurich, Switzerland) at 550 nm to determine absorbance. Blank absorbances were subtracted from sample values and standards were used to create a standard curve to determine POxC concentrations. The following equation was used to determine POXC:

$$POXC\ (mg\ Kg^{-1}\ soil) = [0.02\ mol/L - (B_0 + B_1 \times Abs)] \times (9000mg\ C/mol) \times (0.02L\ solution/Wt)$$

Where:

0.02 mol/L = initial solution concentration

B_0 = intercept of the standard curve

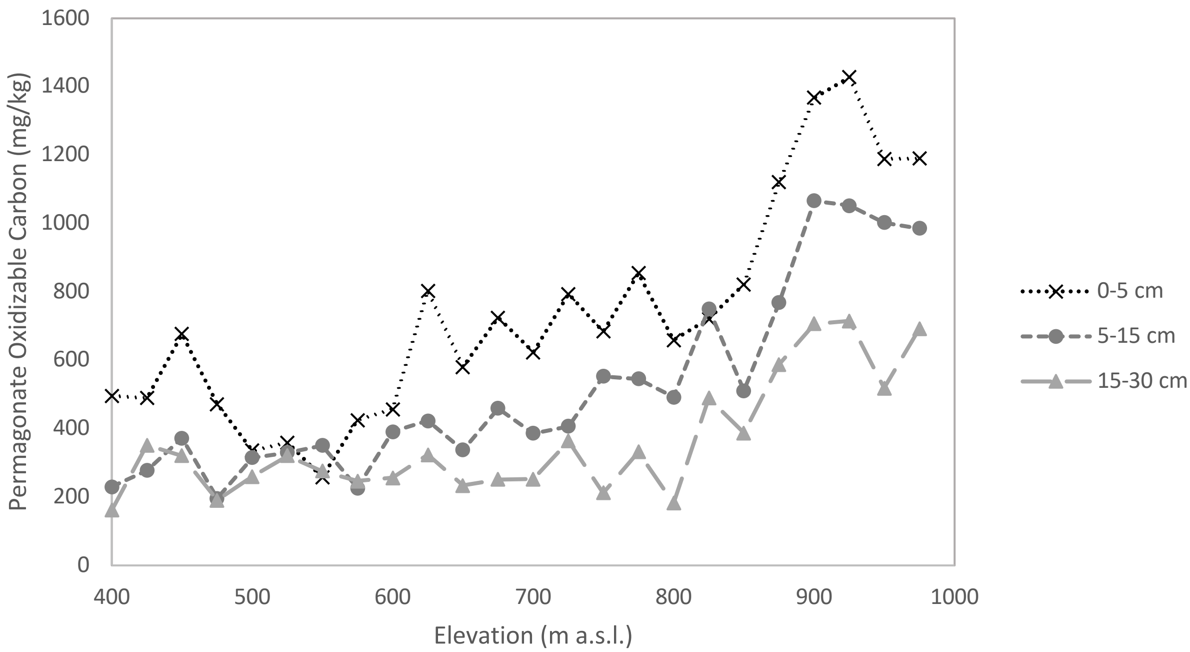
B_1 = slope of the standard curve

Abs = absorbance of the sample

9000 = milligrams of carbon oxidized by 1 mole of MnO_4 changing from Mn^{7+} -> Mn^{4+}

0.02 L = volume of stock solution reacted

Wt = weight of air-dried soil sample in kg



Appendix B-2. Permanganate oxidizable carbon at 0-5, 5-15 and 15-30 cm depth across an elevation gradient at Lac du Bois Grassland in 2019.

Appendix C. Predicting C Stock with LiDAR Derived topographic variables

In grassland ecosystems, topography controls the soil microenvironment, leading to different soil moisture regimes and plant communities (Yoo et al., 2005). Consequently, using topographic variables to predict soil C across grassland ecosystems is a viable approach. High resolution LiDAR generated digital elevation model (DEM) can be used to generate various topographic variables with very high accuracy. Determining relationships between these variables and soil C stocks across semi-arid grasslands will help provide baseline information to make accurate predictive models. The objective of this study was to determine relationships between LiDAR derived topographic variables and soil C stock at the 0-30 cm depth across the southern aspect of an elevation gradient from lower to upper grasslands at Lac du Bois Grassland in the Southern Interior of British Columbia (BC).

Data for the variables listed in Table C-1 were calculated from the LiDAR generated DEM using various tools on ArcGIS and SAGA GIS software platforms. A full list of variables can be seen in Table C-1. A Principal Component Analysis (PCA) on all generated topographic variables was completed to summarize the variability of these properties in the Brown, Dark Brown and Black Chernozem zones.

Relationships between landscape variables and soil C stock were determined using stepwise regression analysis. To try and tease out relationships, models which minimized for BIC and CV error were all considered and compared. The maximum number of variables was set to six to restrict overly complicated models from being produced.

Table C-1. List of topographic variables calculated on Arc-GIS from a LiDAR generated 3-m resolution digital elevation model of Lac du Bois Grassland. short

Abbreviation	Variable
Aspect	Aspect
Catch	Total Catchment Area
CNBL	Channel Network Base Level
CND	Channel Network Distance
Conv_IN	Convergence Index
CTI	Compound Topographic Index
Curvature	Curvature
DAH	Diurnal Anisotropic Heating
Elevation	Elevation
HLI	Heat Load Index
LS-Factor	Slope Length and Steepness Factor
Plan Curv	Plan Curvature
Prof Curve	Profile Curvature
RSP	Relative Slope Position
Slope_Deg	Slope (Degrees)

TRASP	Topographic Solar-Radiation Index
TWI	Topographic Wetness Index
V._Depth	Valley Depth

Soil C stock increased across the grassland elevation gradient from 2.87 kg/m^2 at the lowest to 8.52 kg/m^2 at the highest elevation (Fig. 2-4). In the Brown Chernozemic zone that ranged from 400 to 650 m asl, soil C stock initially starts high and then drops before it starts increasing again. Through the Brown Chernozemic zone (present from 650 to 825 m asl), we see a steady, linear increase in C stock. Finally, in the Black Chernozemic zone (present from 825 to 1000 m asl), we see more clustered, high C stock values.

The principal component analysis (PCA) showed strong overlap among the three Chernozemic great groups in the LiDAR generated topographic variables (Fig. C-1). This was to be expected as our sampling locations were picked to minimize variation in slope, aspect, slope length and position and curvature across the elevation gradient. This means that only very small variation in topographic variables should exist, apart from a constant increase in elevation across the gradient.

Elevation and Channel Network Base Level (CNLB) were tightly grouped and showed the strongest separation of the three great groups along PCA axis 1 (Fig. C-1). All other LiDAR variables were pointing in other directions. This indicates that the other LiDAR variables were related with non-elevation features on the landscape at Lac du Bois.

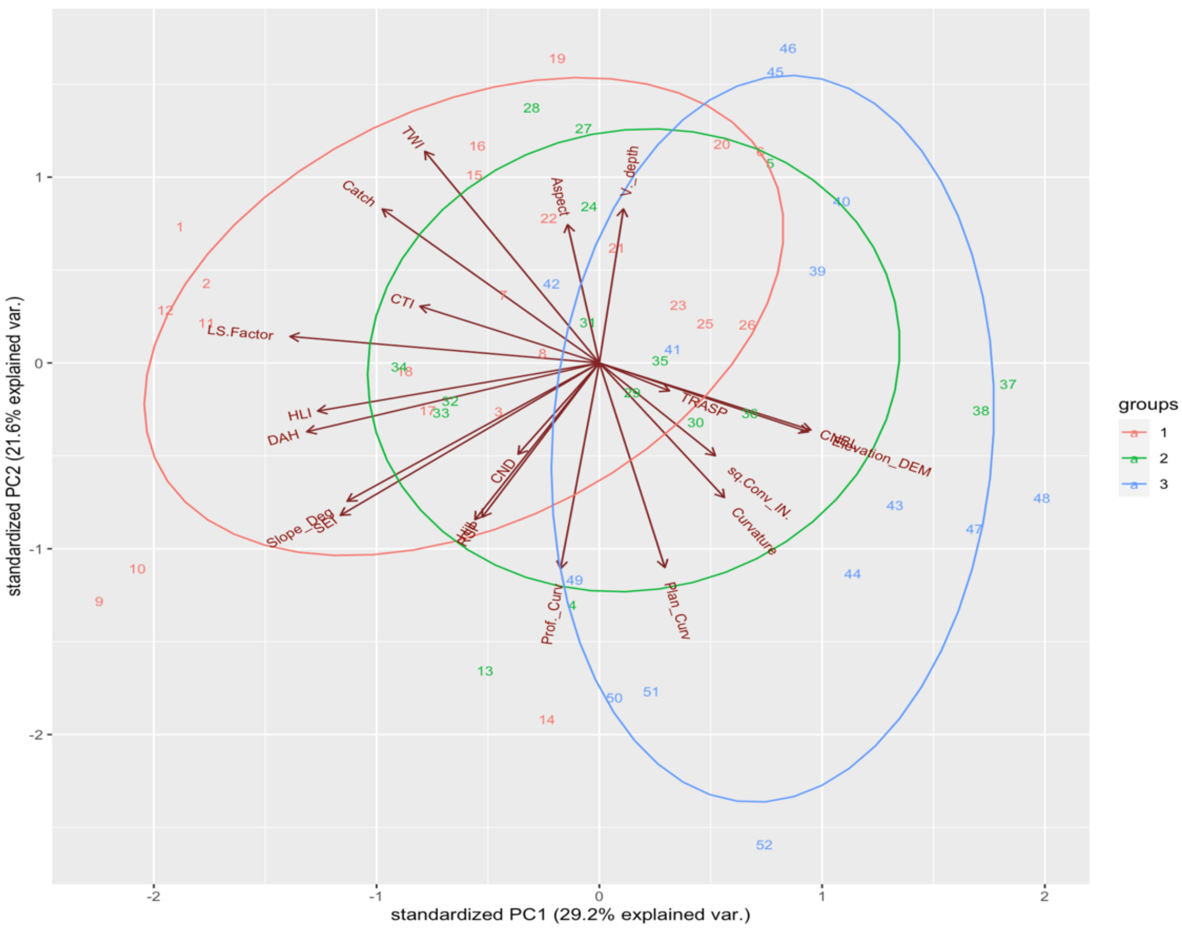


Figure C-1 Principal component analysis (PCA) with LiDAR derived variables listed in Table 3-1, grouped by the Brown (1-red), Dark Brown (2-green) and Black (3-blue) Chernozems at the Lac du Bois Grassland. Numbers indicate soil C stock sample sites.

Forwards and backwards stepwise regression analyses were used to determine relationships between topographic variables and soil C stock in the top 30 cm (Table C-2 to C-5). Starting with 18 topographic variables that might theoretically be good predictors of soil C stock across semiarid landscapes, a forwards and backwards stepwise logistic model was used to determine which variables may be worth exploring further. Models were generated for all C stock observations across the Lac du Bois Grassland as well as for soil C stock observations organized by Chernozemic great group. A few interesting relationships can be seen in these generated models. Elevation appears in four of the six models for the full grassland as well as the

Dark Brown Chernozemic zone. This is to be expected as the Brown and Black Chernozemic zone did not show linear soil C stock increases with elevation, whereas this was seen in the Dark Brown Chernozemic zone. Another interesting observation was that Channel Network Base Level (CNBL) and Valley Depth (VD) have been identified as the best predictors for soil C stock for one-variable models and also for some two-variable models. Both CNBL and VD are associated with locations where water flows across the grassland and as its groundwater, and CNBL specifically predicts how close a sampling site is to groundwater. This emphasizes the importance of water access for soil C stock at the Lac du Bois Grassland.

It is important to note that this type of regression analysis only tries to minimize CV and BIC and maximize R^2. It does not take into account the meaning of each variable and how they could interact with each other. It is also important to note that this study only focused on the southern aspect of the Lac du Bois Grassland. The best models for each prediction area are shown in Table C-6.

Table C-2. Summary of models generated using forwards and backwards stepwise regression analysis for 1 to 6 variables predicting soil carbon () stock at 0-30 cm depth across the whole Lac du Bois Grassland, minimizing CV error, BIC and maximizing R^2 (n=52).

# of Variables	Aspect	Catch	CNBL	CND	Conv IN	CTI	Curvature	DAH	Elevation	Hill	HLI	LS Factor	Plan Curv	Prof. Curv	RSP	SEI	Slope Deg	TRASP	TWI	V. Depth
1			X																	
2			X																	X
3									X						X		X			
4								X	X						X		X			
5								X	X		X				X		X			
6						X		X	X		X				X		X			

Table C-3. Summary of models generated using forwards and backwards stepwise regression analysis for 1 to 6 variables predicting soil carbon (C) stock at 0-30 cm depth across the Brown Chernozemic soils at the Lac du Bois Grassland, minimizing CV error, BIC and maximizing R^2 (n=22).

# of Variables	Aspect	Catch	CNBL	CND	Conv IN	CTI	Curvature	DAH	Elevation	Hill	HLI	LS Factor	Plan Curv	Prof. Curv	RSP	SEI	Slope Deg	TRASP	TWI	V. Depth
1																				X
2				X																X
3		X												X			X			
4		X					X					X								X
5		X					X									X		X	X	
6		X					X					X				X		X	X	

Table C-4. Summary of models generated using forwards and backwards stepwise regression analysis for 1 to 6 variables predicting carbon stock to 30cm across the Dark Brown Chernozemic soils at Lac du Bois grassland, minimizing CV error, BIC and maximizing R^2 (n=16).

# of Variables	Aspect	Catch	CNBL	CND	Conv IN	CTI	Curvature	DAH	Elevation	Hill	HLI	LS Factor	Plan Curv	Prof. Curv	RSP	SEI	Slope Deg	TRASP	TWI	V. Depth
1			X																	
2			X						X											
3			X						X	X										
4									X	X					X					
5						X	X		X	X					X					
6					X	X	X				X						X			X

Table C-5. Summary of models generated using forwards and backwards stepwise regression analysis for 1 to 6 variables predicting carbon stock to 30cm across the Black Chernozemic soils at Lac du Bois grassland, minimizing CV error, BIC and maximizing R^2 (n=14).

# of Variables	Aspect	Catch	CNBL	CND	Conv IN	CTI	Curvature	DAH	Elevation	Hill	HLI	LS Factor	Plan Curv	Prof. Curv	RSP	SEI	Slope Deg	TRASP	TWI	V. Depth
1			X																	
2			X													X				
3			X					X			X									
4		X								X		X						X		
5		X							X	X		X						X		
6								X		X		X	X			X			X	

Table C-6. Predictive models for Carbon Stock across all of Lac du Bois as well as split between the three Chernozemic great groups, created using forwards and backwards stepwise regression analysis, minimizing CV error, BIC and maximizing R^2.

Coverage	Model	Adjusted R^2	F-stat	p-value
Lac du Bois	OC_Stock_30 = -35.599057 + 0.0061398(Elevation) + 55.152461(HLI) + 0.707793(Slope Deg) -1.94011(RSP) - 65.15463(DAH)	0.7343	29.19 on 5 and 46 DF	3.262e-13
Brown Chernozems	OC_Stock_30 = 35.381479 + 0.380880(SEI) - 1.02926327(CTI) -79.74890276 (TRASP) - 0.01573932 (Catch) + 2.25959511(TWI) + 1.05331634(LS Factor)	0.7704	12.74 on 6 and 15 DF	3.818e-05
Dark Brown Chernozems	OC_Stock_30 = -9.30243891 + 0.004890(Elevation) + 0.380948(CTI) + 0.159541(Curvature) + 9.00374(Hill) - 1.36243093(RSP)	0.8064	13.5 on 5 and 10 DF	0.0003543
Black Chernozems	OC_Stock_30 = -17.460262 + 68.23343(TRASP) -15.83160(Hill) - 0.015310(Catch) + 3.89237(LS.Factor)	0.8474	19.04 on 4 and 9 DF	0.0002036

Principal component analysis showed that elevation and Channel Network Base Level (CNBL) were the two LiDAR derived topographic variables most strongly correlated with the variation in soil C stock among the three different Chernozemic great groups across the Lac du Bois Grassland. However, the majority of topographic variables calculated from a LiDAR generated 3-m resolution digital elevation model appeared to be more strongly related to soil C stock variation within, rather than between, the Chernozemic great groups. This was not surprising as the sampling regime attempted to minimize the variation in many of these topographic variables across the elevation gradient. The distance to ground water (Channel Network Base Level) was also identified as an important predictive variable in several of the regression models, showing the importance of access to water in the formation of soil C stocks.

Overall, the regression results have highlighted a number of topographic variables that show promise as predictors of soil C stocks in semiarid grasslands.