THE EFFECTS OF PRECIPITATION AND CLIPPING ON CARBON SEQUESTRATION IN TEMPERATE GRASSLANDS

By

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ABSTRACT

Grasslands are a small but significant component of British Columbia's ecosystems. Although they represent less than 1% of the province's land base, they provide critical habitat for over 30% of BC's threatened and endangered species. Grasslands not only provide habitat for a wide variety of species, but they also provide a significant forage base for BC's ranching industry. A variety of factors such as urban expansion, subdivision and development, agricultural conversion, abusive recreation, inappropriate land management practices, non-native invasive plants and forest encroachment are threatening grasslands. Climate change has potential implications too, as it affects productivity and biodiversity of grasslands. I investigated the potential of temperate grasslands in the Southern Interior of British Columbia to sequester carbon. Carbon content and Net Carbon Exchange rates of different elevation grasslands in Lac du Bois Park were evaluated under different precipitation and management treatments. Carbon storage of fall vs. spring-grazed pastures was evaluated as well. The results of the field experiments showed that increase in frequency of fall precipitation events leads to corresponding increase in carbon levels of soil. Clipping treatment at 5 cm stubble height showed decrease of carbon content at upper elevation grasslands. Net Carbon Exchange rates tended to vary during the growing season, with the highest rates recorded in July. More frequent spring precipitation events increased respiration rates considerably, resulting in carbon loss from soils. Grazing during fall at the middle elevation resulted in higher carbon content of soils, when Net Carbon Exchange values were higher for spring grazed pastures. The results of field experiments have been used to estimate the carbon storage profit potential of Lac du Bois grasslands. The Carbon Profit Potential model was developed to represent the monetary value of grassland carbon. The outputs of the model showed that the current value of Lac du Bois Grasslands is 4.46 million dollars in terms of stored carbon, and this value could be increased annually by $0.48 million if rainfall events occur more often during fall. High stocking rates are not recommended for upper elevation grasslands as it resulted in $0.325 million decrease in profits. Although these values are an underestimate it provides a base line for grassland carbon estimations in British Columbia and indicates that grassland carbon might be a significant part of carbon market.

Keywords: grassland carbon, carbon content, ecosystem services, climate change, grazing

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Chapter 1 - General information

Introduction

Carbon dioxide emissions from the burning of fossil fuels are the main cause of climate change (Hansen et al. 2006). The atmospheric concentration of carbon dioxide is increasing due to human activities. Climate change results from greenhouse gas (GHG) emissions associated with economic activities, like energy production, industrial development, transport and land use (Stern 2006). Mitigation of climate change and, as a consequence, abatement of GHG emissions has been an international concern, resulting in the 1997 Kyoto Protocol – the first international agreement that set emission benchmark and allocated targets to the participating countries. In 2001, the Marrakesh accord allowed the use of biosphere “sinks” and emission trading in order to meet reduction targets. Additional carbon sequestration that is eligible as abatement included storage in biomass and soil, management of agricultural lands and forests. Most carbon sequestration projects considered forests and agricultural lands as a potential carbon “sink”. Although these ecosystems are capable of storing considerable amounts of carbon, they are more vulnerable to short-term carbon release. Grasslands, however, might be a reliable, long-term carbon “sink” due to the biology of grassland carbon sequestration. Forests store large amounts of carbon in the above-ground woody biomass, while grasslands use biomass as a bridge between atmospheric carbon and soil, so that most sequestration in grasslands occurs in the soil. Considering that grasslands are the second largest terrestrial ecosystem in the world (Mannetje 2007), its inclusion into sequestration projects might be viable (Tennigkeit and Wilkes 2008).

Grasslands are a small but significant component of British Columbia’s ecosystems. Although they represent less than 1% of the province’s land base, they provide critical habitat for over 30% of BC’s threatened and endangered species. BC’s grasslands are considered one of Canada’s most endangered ecosystems. Grasslands not only provide habitat for a wide variety of species, but they also provide a significant forage base for BC’s ranching industry. Roughly 90% of BC's grasslands are grazed by domestic livestock, either through deeded private rangelands, grazing tenures on provincial crown land or grazing regimes on First Nations land (GCC Report 2004). A variety of factors such as urban expansion, subdivision and development, agricultural conversion, abusive recreation, inappropriate land management practices, non-native invasive plants and forest encroachment are threatening grasslands. Climate change has potential implications too, as it will affect the productivity and biodiversity of grasslands.

From an economic point of view, ecosystem services of grasslands have a value that affects policy decisions. Carbon sequestration costs or benefits need to be considered in the valuation of grassland services. A lot of work has been done in estimating the forest potential for carbon sequestration, and putting a value to the forest carbon sequestration (Costanza et al. 1997, Deveny 2009). Fewer studies have estimated grasslands capacity as a "carbon sink", much less attempt to put a dollar value to grassland carbon.

Today policymakers are trying to convert "carbon sinks" into marketable value by means of Carbon Banking and Trading. For this purpose data about possible "carbon sinks" is required. The lack of information about biological aspects of carbon sequestration by grasslands and the unknown effects of management and climate change on the potential for carbon storage needs to be addressed.

My study discovers the potential of British Columbia's grasslands to sequester carbon and attempts to evaluate ecosystem services of carbon sequestration.

Aims and Structure of the Thesis

My thesis examines the effect of climate change and management treatments on carbon storage of different grassland types at Lac du Bois Grasslands Provincial Park. Furthermore I develop an economic model for estimating grassland carbon profit potential. I have organized my thesis into the following chapters:

Chapter 1: General introduction. This chapter introduces the ideas examined throughout the thesis.

Chapter 2: Effects of Rainfall Manipulations and Clipping on Soil Carbon Content and Net Carbon Exchange in Temperate Grassland. This chapter describes soil carbon pools and the dynamics of carbon exchange in three different grassland types that vary in site productivity, and examines how different precipitation patterns and clipping may influence carbon storage. The effects of different grazing practices on carbon content of middle elevation grasslands are evaluated further in this chapter.

The following hypotheses are tested:

(1) High elevation (upper) grasslands have higher soil carbon pools than low elevation grasslands.

(2) A decrease in soil water availability will decrease the soil carbon load and potential for carbon sequestration. Particularly, decreases in spring precipitation compared to fall precipitation will result in lower rates of carbon deposition to the soil.

(3) Clipping (a surrogate of grazing) will decrease Net Carbon Exchange that will result in carbon deposition into the soil.

(4) Fall-grazed pastures have the potential to store more carbon than spring-grazed pastures.

Chapter 3: Economic Assessment of Grassland Ecosystem Services and Development of Grassland Profit Potential Model: the case of Lac du Bois Grasslands. Here I determine the economic value of grassland ecosystem services for temperate grasslands of British Columbia using the grasslands in Lac du Bois Provincial Park as a case study. The Grassland Carbon Profit framework (GCPF) has been developed to represent this value.

GCPF combines biological and economic components. The biological component is represented by grassland carbon quantity, while the economic component is represented by price of carbon, opportunity costs of the land and discounting rate. Separate models have been developed for grassland carbon quantity and opportunity costs of the land. The justification for adopted carbon price and discounting rate is also provided.

Chapter 4: General Conclusions, Management Implications and Recommendations for Future Research. This chapter summarises results, outlines future directions for research, and discusses management and policy implications of this study.

Chapter 2 – Effects of Rainfall Manipulations and Clipping on Soil Carbon Content and Net Carbon Exchange in Temperate Grassland

2.1 Introduction

Studies examining global temperatures over the past millennia indicate that surface temperatures have increased by approximately 0.6^{o} Celsius in the past 30 years (Hansen et al. 2006; IPCC Report 2007). It is estimated that Earth's current surface temperature is as warm as it was at the Holocene maximum (Hansen et al. 2006) and the 20th century is considered the warmest century of the past millennium (Jones and Mann 2004).

Industrialization and production of fossil fuels, as well as land use changes (i.e., deforestation), have resulted in increased amounts of carbon dioxide and other greenhouse gases (GHG) in the atmosphere (Hansen 2008). These gases intensify the process of global warming, which causes changes in ecosystem structure and properties (Hitz and Smith 2004). Increases in atmospheric CO_2 concentration and mean annual global temperature have caused alterations in mean annual global precipitation (Meehl et al. 2007). A key prediction of altered precipitation is an increased risk of drought (Reichstein et al. 2007). In grassland ecosystems, water is the major limiting factor, therefore changes in precipitation patterns and increased risk of drought will likely have a major impact on grassland ecosystems. Grasslands may therefore be affected by global warming through drought and the ensuing soil erosion, accompanied by a decrease in biodiversity and ecosystem degradation (Winslow et al. 2003; Li et al. 2004; Rustad 2008).

Grasslands are among the largest ecosystems in the world. Their area is estimated at 52.5 million square kilometres, or 40.5 percent of the terrestrial area excluding Greenland and Antarctica. Of this terrestrial area, 13.8 percent (excluding Greenland and Antarctica) is woody savannah and savannah; 12.7 percent is open and closed shrub; 8.3 percent is non-woody grassland; and 5.7 percent is tundra (Suttie and Reynolds 2005). One of the largest tropical and subtropical grasslands is the Llanos of South America. The largest temperate grasslands are the Prairie and Pacific Grasslands of North America, Pampas of Argentina, Brazil and Uruguay, and the steppes of Europe. Grasslands provide essential habitat for insects, birds and small animals, and forage for cattle and other herbivores. Large areas of grassland have been converted into agricultural land for food production (Carlier and Rotar 2009).

Grasslands are of major importance for maintaining Earth’s carbon cycle (Parton et al. 1995). Almost 34 percent of the terrestrial stock of carbon is stored in grasslands, including soil carbon, litter and plant biomass, which is almost equal to the amount stored by forests (Wilson 2009). However the mechanism underlying carbon sequestration in soils remains unclear (Rustad 2008). Primary productivity as an input and soil respiration as an output are among the processes that influence soil carbon pools (Amundson et al. 2001). de Deyn et al. (2008) discuss the importance of plant functional traits on carbon sequestration, particularly relative growth rate. The authors suggest that plants with high relative growth rate lead to higher carbon content of soils than plants with low relative growth rate. The relationship between plants and mycorrhizal fungi is important for carbon accumulation because it can increase plant productivity through enhanced acquisition of limiting resources (de Deyn et al. 2008). Soil respiration is the main source of carbon loss in the soil. It results from metabolic activity of autotrophs and heterotrophs (Hogberg and Read 2006). Carbon loss through plants occurs in two major ways, the first is through root respiration and volatile organic carbon release and the second is through the rates at which heterotrophs decompose, assimilate and respire plant-accumulated carbon (de Deyn et al. 2008).

Environmental factors influence the rate of soil carbon sequestration. Therefore, climate change will likely affect carbon sequestration. Most climate change models for British Columbia (B.C.), Canada predict increasing temperatures and precipitation during winter, and increased periods of drought during summer (Hamman and Wang 2005; Gayton 2008). For grasslands in B.C., climate change scenarios predict expansion to new biogeoclimatic zones and increases in diversity, especially for weedy species (Long and Hutchin 1991; Hamman and Wang 2005). Primary production is the factor that links climate change and soil carbon sequestration. Grasses respond to the increasing temperatures and precipitation by intensive photosynthetic activity and primary production. Flanagan et al. (2002) studied the inter annual variation of carbon stocks in a northern temperate grasslands (Alberta) and found increases in soil carbon stocks during wet years, which was related to increased primary productivity of plants. There are other possible influences climate change can inflict on ecosystems that will result in decreases in primary productivity. For example, lack of water, due to increased temperature and evaporation, can increase soil erosion and may reduce plant productivity (Rustad 2008). A reduction in plant productivity can limit the quantity and quality of forage for the ranching industry, thus affecting the economic value of grasslands. Reduced forage for livestock may lead to overgrazing, which can cause losses in species diversity, an increase in undesirable non-native invasive plants and a further reduction in soil quality (Bremer 2001; Conant et al. 2001; Rees et al. 2005).

The goal of my project is to study soil carbon pools and the dynamics of carbon exchange in three different grassland types that vary in site productivity, and how different precipitation patterns may influence carbon storage. Once we understand carbon dynamics in grasslands new management practices can be tested to maximize carbon storage and to offset global carbon emissions (Shrestha and Stahl 2008). Appropriate management could increase the input of organic carbon in soils and decrease the losses from soil respiration and erosion (Tennigkeit and Wilkes 2008). Furthermore, there is the potential for marketable carbon credits resulting from grazing management practices aimed at increasing carbon storage (Rees et al. 2005; Fleischer and Sternberg 2006).

My research explored the capacity of temperate grasslands in the southern interior of British Columbia, Canada to sequester carbon. Two experimental studies were designed to test the potential of grasslands for carbon storage.

The first study was a controlled rainfall manipulation experiment with three hypotheses:

(1) High elevation (upper) grasslands have higher soil carbon pools than low elevation grasslands;

(2) A decrease in soil water availability will decrease the soil carbon pools and potential for carbon sequestration. Particularly, decreases in spring precipitation compared to fall precipitation will result in lower rates of carbon deposition to the soil.

(3) Clipping (a surrogate for grazing) will decrease Net Carbon Exchange that will result in carbon deposition into the soil.

The second study was conducted in a long-term, ~10-year grazing management trial that included two pastures, one that was spring-grazed and the other that was fall-grazed. I tested the hypothesis that fall-grazed pastures have the potential to store more carbon than spring-grazed pastures.

2.2 Materials and Methods

2.2.1 Site description

The research was done at Lac du Bois Grassland Provincial Park located to the north-west (50°40'34"N; 120°20'27"W) of the city of Kamloops, British Columbia, Canada. Lac du Bois is approximately 3300 ha of grasslands, wetlands and forests ranging in elevation from 350 to 1000 m above sea level (Fraser et al. 2009).

The climate in Lac du Bois Park is highly variable from year to year. Average annual precipitation at Kamloops is about 260 mm and increases to 310 mm with the increase of elevation towards the forests in the highest parts of the park (Carlyle et al. 2011). The driest months are March and April, with most of the rain falling in June and August, often in the form of thunderstorms (Ministry of Environment, Lands and Parks Report 2000) (See Appendix). Most of the snow falls in December and January. The average annual temperature in the valley bottom is 8.4° C and decreases by 0.5 degree for every 500 m increase in elevation (Ministry of Environment, Lands and Parks Report 2000). In general, Lac Du Bois grasslands at greater altitude (upper elevation) have higher precipitation and lower mean temperatures (Tisdale 1947; van Ryswyk et al. 1966).

Topography of the park is highly variable due to underlying geology, glaciations and glacial deposits (Ministry of Environment, Lands and Parks Report, 2000). van Ryswyk et al. (1966) described it as “irregular being marked by small benches and deep gullies”. Glacial processes directly influenced the surface structure. Stones that are common below 490 m are a result of glacial till deposits subjected to wind and water erosion (van Ryswyk et al 1966).

Climatic and geological processes played an important role in developing the soils in Lac du Bois (Lee 2011). According to Canadian Soil Classification System (Soil Classification Working Group 1998) soils of the park consist predominately of Chernozems (van Ryswyk et. al. 1966). Chernozemic order of soils is comprised by four great groups based on morphological characteristics: Brown, Dark Brown, Black and Dark Grey (van Ryswyk et al. 1966, Soil Classification Working Group 1998). Brown Chernozems typically have a coarse substrate which leads to the dry, well-drained, species poor soils recognized as the lower grasslands. Dark Brown Chernozems are soils consisting of gravely tills which results in slightly better moisture retention. These soils characterize the middle grasslands or moister areas of the lower grasslands, and represent the transition zone. Black Chernozems are composed of finer grained tills resulting in the deeper organic layer of the upper grasslands (Ministry of Environment, Lands and Parks Report 2000). Dark Grey Chernozems are most commonly found in the transition zone between forests and grasslands. These soils are recognized as silty loams and tend to be well drained (Valentine and Lavkulich 1978).

The vegetation of the Lac Du Bois Park is highly diverse and ranges from semi-arid grasslands to dry Ponderosa pine (*Pinus ponderosa)* and Douglas fir (*Pseudotsuga menziesii*) forests. Of the fourteen Biogeoclimatic Zones in British Columbia, the park grasslands are represented by three: Bunchgrass Zone, Ponderosa Pine Zone and Interior Douglas Fir Zone (Ministry of Environment, Lands and Parks Report 2000). Plant communities within the park area have been classified into Lower, Middle and Upper grasslands (Spilsbury and Tisdale 1944; Tisdale 1947). Lower grasslands mainly consist of bluebunch wheatgrass (*Agropyron*) and big sagebrush (*Artemisia*) communities (van Ryswyk et al. 1966). Middle grasslands are represented by bluebunch wheatgrass; and upper grasslands are highly diverse and dominated by rough fescue, junegrass and Kentucky bluegrass (Lee 2011). Rough fescue also can be found at the lower and middle grasslands on the north-facing slopes (Lee 2011).

The research sites for the first experiment involving rainfall manipulations were selected to represent differences in elevation, climate and plant communities. Experimental plots were established at three locations (lower, middle and upper grassland types) in the park, as shown on the map (Fig. 2.1). The second study to assess the effects of spring versus fall grazing on carbon storage was done at the middle grassland (Fig. 2.1).

Figure 2.1. Map of Lac du Bois Provincial Park. Red stars indicate locations of the first experimental study (rainfall manipulations); blue stars indicate location of second study (spring and fall grazing). Letter abbreviations refer to elevation: LE – lower; ME – middle; UE - upper.

For the first study, three 30 m × 50 m fenced exclosures were established at the low, middle and upper elevation to restrict cattle grazing. Within each of tree exclosures 72 1 m × 1 m plots were established. For the second study a 90 m transect was established on the spring grazed and fall grazed pastures, representative of plant communities, soil type and similar topography.

2.2.2 Experimental design

The duration of the experiment was two growing seasons starting in May 2009 and finishing in November 2011.

The study was designed as a part of a larger experiment aimed to test how controlled precipitation manipulations and clipping affect the plant community and soil properties of the different grassland types in Lac du Bois. Twelve different treatments (1 block) were selected to represent potential climate change and grazing scenarios. Each treatment was replicated 6 times. Amount of water added to the plots were calculated on the base of monthly averages for the last thirty years, plus fifty percent increase to compensate for the rain shading effect of the shelters and predicted increases in fall-winter precipitation according to the climate change models for BC (Loukas et al. 2001). During the two ‘summer’ months (July and August) all rain shades were taken down (i.e. climate conditions were ambient in the summer).

Twelve treatments were implemented: 1) control plot, no treatment was applied to this plot; 2) clipping control plot, only clipping treatment was applied; 3) rain shade control plot, shredded (sliced*)* rain shades (considered as a rain shade controls) were installed to determine if rain shades have influence on the environmental factors (soil moisture and temperature); 4) rain shade plus clipping control, to determine if interaction of two factors affects soil moisture and temperature; 5) Spring water addition on a weekly basis; 6) Spring water addition on a weekly basis plus clipping; 7) Spring water addition on a monthly basis; 8) Spring water addition on a monthly basis plus clipping; 9) Fall water addition on a weekly basis; 10) Fall water addition on a weekly basis plus clipping; 11) Fall water addition on a monthly basis; 12) Fall water addition on a monthly basis plus clipping. All plots, except one and two (control and clipping control), had rain shades installed during watering periods, to block natural precipitation (Table 2.1). The two Spring months included May and June, while the Fall months were September and October.

Table 2.1. Experimental design of the study

Treatm.	**Water addition**				**Rain shades**		**Clipping**
	Spring		**Fall**		**Spring**	**Fall**	
# of plot	**Weekly**	**Monthly**	**Weekly**	**Monthly**			
1	-	-	-	-	-	-	-
2	-	-	-	-	-	-	▨
3	-	-	-	-	▨	▨	-
4	-	-	-	-	▨	▨	▨
5	▨	-	-	-	▨	▨	-
6	▨	-	-	-	▨	▨	▨
7	-	▨	-	-	▨	▨	-
8	-	▨	-	-	▨	▨	▨
9	-	-	▨	-	▨	▨	-
10	-	-	▨	-	▨	▨	▨
11	-	-	-	▨	▨	▨	-
12	-	-	-	▨	▨	▨	▨

Construction of rain-out shades followed the same design as Fraser et al. (2009). A 1 m^2 plastic sheet was attached to a pole 1 m high at one corner and anchored at the remaining three corners such that they were each 0.3 m above soil surface to allow airflow. The sheets were oriented to block rain from the dominant wind directions during the growing season – the East and West (Fig. 2.2).

Figure 2.2. Experimental plot with rain-out shade (photo by J. McCulloch)

Clipping manipulations represented disturbance to the plant communities that usually occurs on the rangelands in the form of grazing. The clipping of plots was done in the middle of the growing season between late June and early July. Vegetation was clipped to a height of 5 cm. This height of clipping represents a typical post-grazed stubble height in heavily grazed rangelands (Ministry of Agriculture Food and Fisheries, 2005; Bailey et al. 2010).

The second study was conducted on the middle grasslands in fall-grazed and spring-grazed pastures. A long term study was initiated approximately ten years ago where one pasture was consistently spring grazed every year while the other was fall grazed. A 100 m transect was randomly established on each pasture to test differences in soil carbon content and Net Carbon Exchange (NCE).

2.2.3 Sampling, Measurements and Analysis

For the first experimental study, soil samples were collected in May 2009, before commencement of the treatments, and at the end of each growing season: October 2010 and 2011. The measurements of Net Carbon Exchange (NCE) were ongoing during both growing seasons. The soil moisture and temperature data was recorded for the length of the experiment, excluding winter months (see Appendix). For the second study, soil samples were collected and NCE measurements were done in August 2011.

Sample collection and measurements

For the first experimental study, one soil sample was collected from each experimental plot at two depths, 0-15 cm and 15-30 cm, using a soil corer with a 2 cm diameter and 30 cm length. Due to the shallow depth of soils at the middle grassland site, I was not able to sample the 15-30 cm depth of middle grasslands. Soil cores were stored in zip-lock bags and transported to the laboratory where they were air dried. Dry soil samples were sieved with 2mm mesh to separate coarse fragments, roots and small rocks.

For the second study involving spring and fall grazed pastures, one sample was collected along a 90 m transect at every 10 m interval for a total of 10 samples per pasture. The same soil corer was used to sample at 0-15 cm, but shallow soils at the middle elevation grassland site prevented collection of soil samples at 15-30 cm depths. The procedure of readying samples for analysis was the same as in the first experimental study.

One Net Carbon Exchange (NCE) measurement was done on each plot using the LI-8100A Automated Soil CO_2 Flux System (LI-COR Biosciences) (Fig. 2.3). For the second study (spring and fall grazing) a single reading was collected 10 times along the 90 m transect at both the fall and spring-grazed pasture.

Figure 2.3. Automated Li-COR Soil CO2 Flux System in operation

The LI-8100A uses the rate of increase of CO_2 concentration in a measurement chamber to estimate the rate at which CO_2 diffuses into free air outside the chamber (Li-Cor Biosciences, 2010). NCE is defined as the net carbon exchange between ecosystem and the atmosphere, which is the photosynthesis uptake minus the total respiration, including above ground respiration and soil respiration. In the case where no plants were present inside the measurement chamber then measured NCE is soil respiration (Li-Cor Biosciences, 2010).

Sample analysis

Dry and sieved samples were prepared (ground) for analysis for total carbon content. The analysis was performed using an automated elemental analyzer (CE-440 Elemental Analyzer, Exeter Analytical Inc., North Chelmsford, MA) (Fig. 2.4).

Figure 2.4. CE-440 Elemental Analyzer Unit in operation

2.2.4 Statistical Analysis

Statistical analysis of the data was performed using SYSTAT 8.0 statistical software (SYSTAT Software Inc.).Three-way factorial ANOVA models were used, with change in carbon content and Net Carbon Exchange as the variables, and water addition, clipping and elevation as the dependent factors. Separate models were run for each soil depth. Before any statistical analysis was performed, change in carbon content was calculated by finding the difference between results of 2011 and 2010 soil carbon data. To eliminate any negative values the integer number 25 was added to all the data points. Change in carbon content and Net Carbon Exchange data was then logarithmically transformed to increase the normality of distribution. A Tukey post-hoc analysis was performed on the means using R statistical software (Marascuilo and Levin 1970).

2.3 Results

2.3.1 Soil Carbon Pool

Initial carbon content (C) for the 0-15 cm of soil profile at the upper elevation site was approximately two times higher (p = 0.001) than that of lower and middle elevations (p = 0.261) (Fig. 2.5). For the 15-30 cm of soil profile, upper elevation had higher (p = 0.001) carbon content than lower elevation (Fig. 2.5).

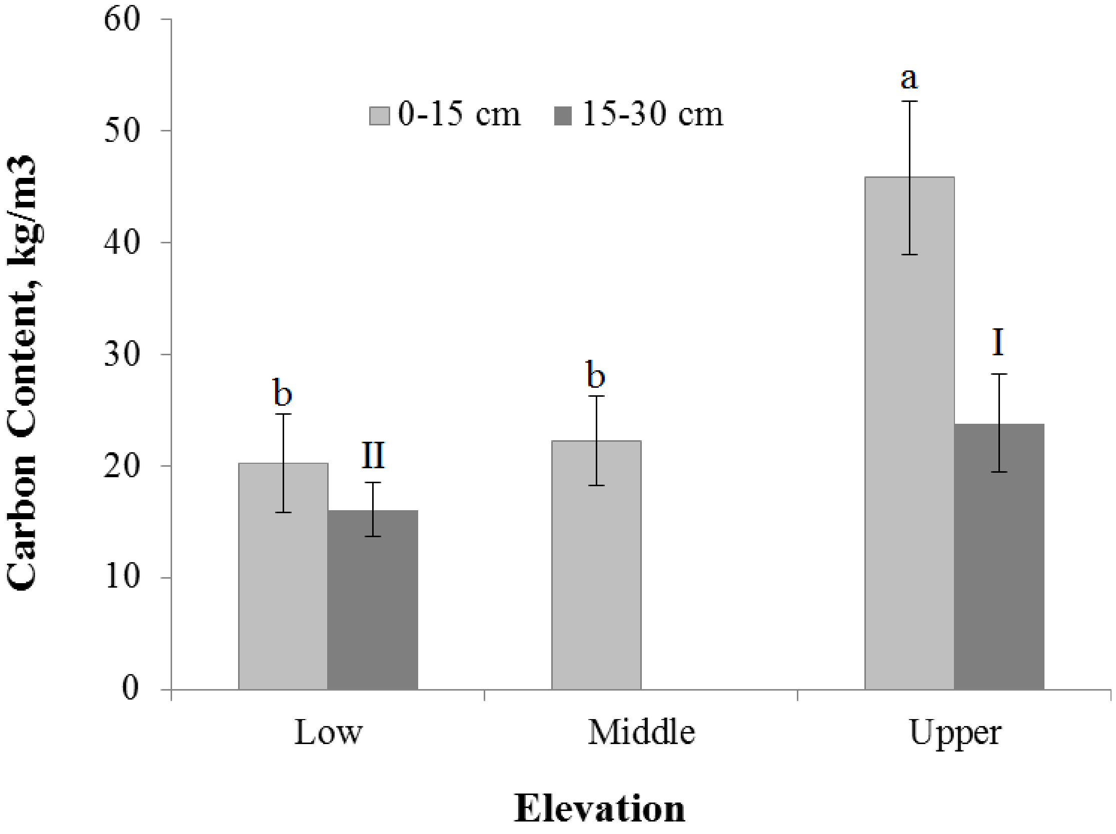


Figure 2.5. Soil carbon content of different grassland types at 0-15 cm and 15-30 cm depths. Error bars represent ±SD. The same letters (a,b) indicate insignificant difference in the mean according to Tukey post-hoc test at first respective depth. The same roman numbers (I, II) indicate insignificant difference in the mean according to Tukey post-hoc test at second respective depth (n=72).

Table 2.2. Three-way ANOVA results to test interacting effects of elevation, watering and clipping on change in soil carbon content (Fall 2010 to Fall 2011) at two depths (0-15 cm and 15-30 cm). Bold indicates significant 3-way ANOVA results at the p < 0.05.

Treatment and Interactions	**Df**	**Soil depth, cm**					
		0-15			**15-30**		
		Mean Squares	**F-ratio**	**P-value**	**Mean Squares**	**F-ratio**	**P-value**
Elevation	2	**0.210**	**16.176**	**3.76 e^{-7}**	**0.083**	**5.579**	**0.021**
Watering	5	**0.030**	**2.309**	**0.046**	0.021	1.466	0.208
Clipping	1	0.009	0.697	0.405	0.001	0.044	0.834
Elevation × Watering	10	0.017	1.345	0.210	0.023	1.571	0.176
Elevation × Clipping	2	**0.043**	**3.375**	**0.036**	0.010	0.652	0.421
Watering × Clipping	5	0.007	0.524	0.758	0.009	0.598	0.701
Elevation × Watering × Clipping	10	0.006	0.445	0.922	0.003	0.195	0.963

Soil carbon content at the 0-15 cm depth was affected by the watering treatments (Table 2.2; Fig. 2.6). According to the 3-way ANOVA and Tukey post-hoc test, weekly fall watering (WEEKFALL) had higher soil carbon content than rain shade control plots (NO). All other treatments had equivalent effects on soil carbon.

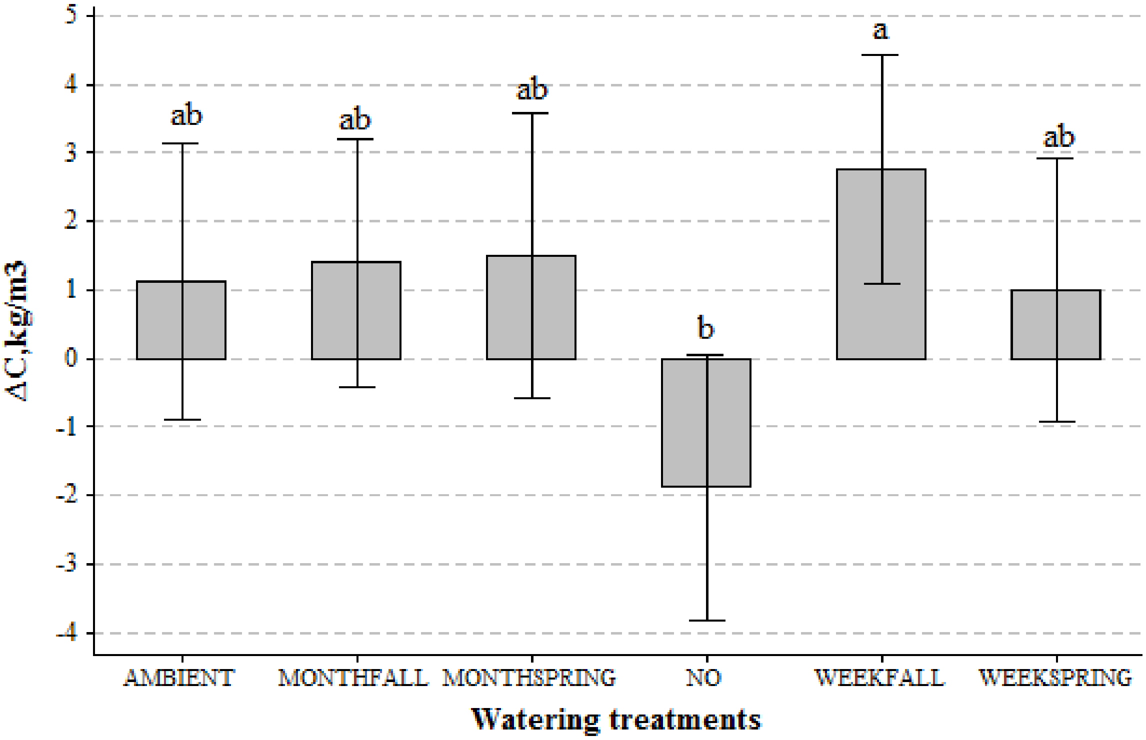


Figure 2.6. Effect of watering treatment on the change in soil carbon content (from fall 2010 to fall 2011) at first respective depth. On the x-axis, 'AMBIENT' is the control (no rain-out shelter), 'MONTH' refers to watering once a month, 'WEEK' refers to watering once per week, 'FALL' refers to watering in September and October, 'SPRING' refers to watering in May and June, and 'NO' refers to plots with shredded (control) rain-out shelters in Fall and Spring but with no watering. Error bars indicate ±SD. Bars sharing the same letter are not significantly different in means according to Tukey post-hoc test.

A significant interaction between elevation and clipping was detected on soil carbon at 0-15 cm soil depth (Table 2.2, Fig.2.7). According to Tukey post-hoc test clipping treatments did not show any significant difference in means within low and middle elevations, as well as between them. Upper plots, that have been clipped, showed considerably higher rates of change (decrease) in carbon content than clipped plots at lower and middle elevation. Change of carbon levels at clipped and unclipped plots at the upper grasslands was not significantly different from each other.

Statistical analysis of carbon content at 15-30 cm depth did not show any significant effect of watering and clipping treatments. Upper grasslands had higher soil carbon content compared to lower grasslands (Table 2.2, Fig.2.5).

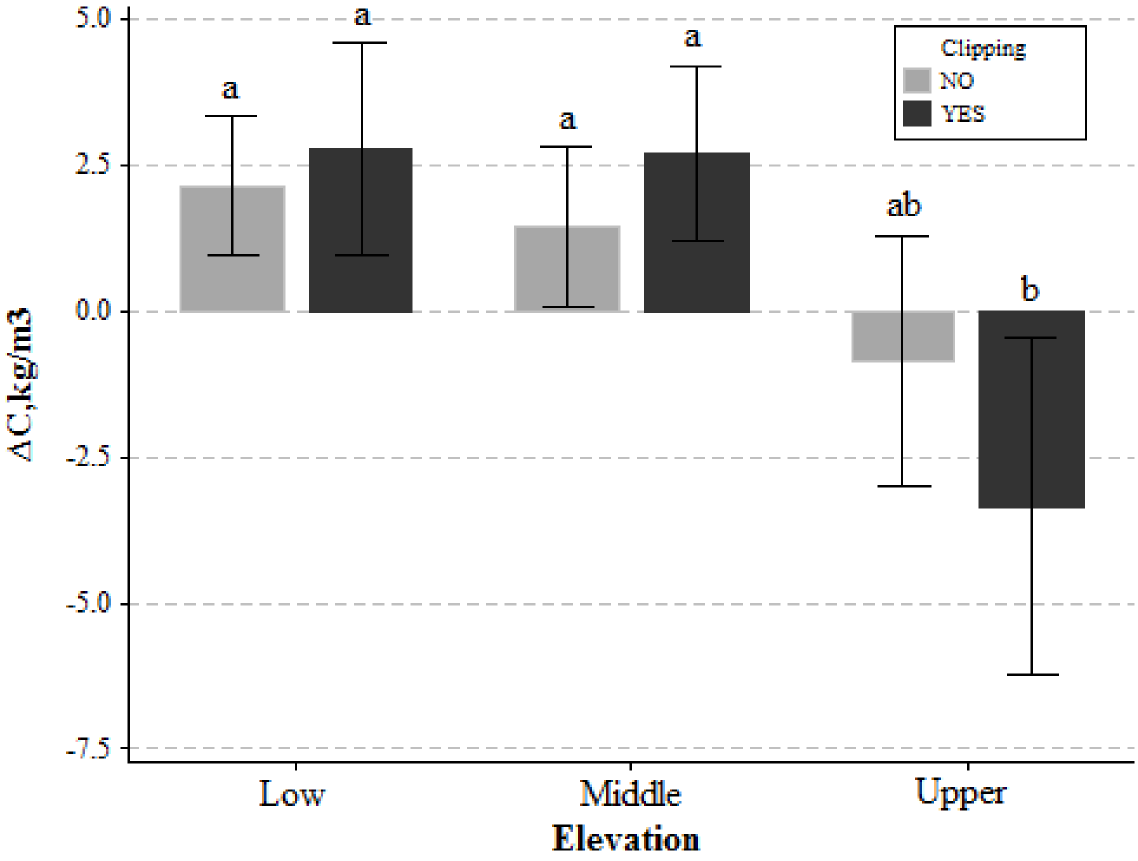


Figure 2.7. Interaction effects of elevation and clipping on soil carbon at 0-15 cm soil depth. Error bars indicate ±SD. Bars sharing the same letters are not significantly different using Tukey post-hoc analysis.

2.3.2 Net Carbon Exchange (NCE)

Net Carbon Exchange (NCE) was affected by elevation, by watering, and by the interaction between elevation and watering (Table 2.3). NCE of upper and middle elevation grasslands was higher than NCE of low elevation grasslands (Fig. 2.8). Net carbon exchange values of upper and middle grasslands were not significantly different from each other according to Tukey post-hoc test.

Table 2.3. F-values and P-values from 3-Way ANOVA to test the effects of elevation, watering and clipping on Net Carbon Exchange based on monthly measurements for 2011. Bold indicates significant results with $p < 0.05$.

Treatments and interactions	**Df**	**May**		**June**		**August**		**September**		**October**		**November**	
		F	**P**	**F**	**P**	**F**	**P**	**F**	**P**	**F**	**P**	**F**	**P**
Elevation	2	**13.729**	**0.000**	**169.469**	**0.000**	**211.804**	**0.000**	**273.482**	**0.000**	**291.897**	**0.000**	**4.300**	**0.016**
Watering	*5*	0.519	0.762	**3.354**	**0.007**	**5.806**	**0.000**	0.958	0.447	1.655	0.152	0.529	0.754
Clipping	1	0.685	0.419	1.671	0.199	2.261	0.112	0.001	0.970	0.751	0.388	0.497	0.483
Elevation × Watering	10	0.611	0.802	1.194	0.303	**2.574**	**0.008**	0.350	0.965	1.139	0.341	0.285	0.983
Elevation × Clipping	2	0.297	0.744	0.119	0.888	0.127	0.881	0.343	0.711	0.889	0.414	0.455	0.636
Watering × Clipping	5	0.680	0.639	1.491	0.199	1.298	0.270	0.564	0.728	0.844	0.522	0.401	0.847
Elevation × Watering × Clipping	10	0.942	0.498	0.874	0.560	1.131	0.346	0.647	0.770	1.222	0.285	0.238	0.992

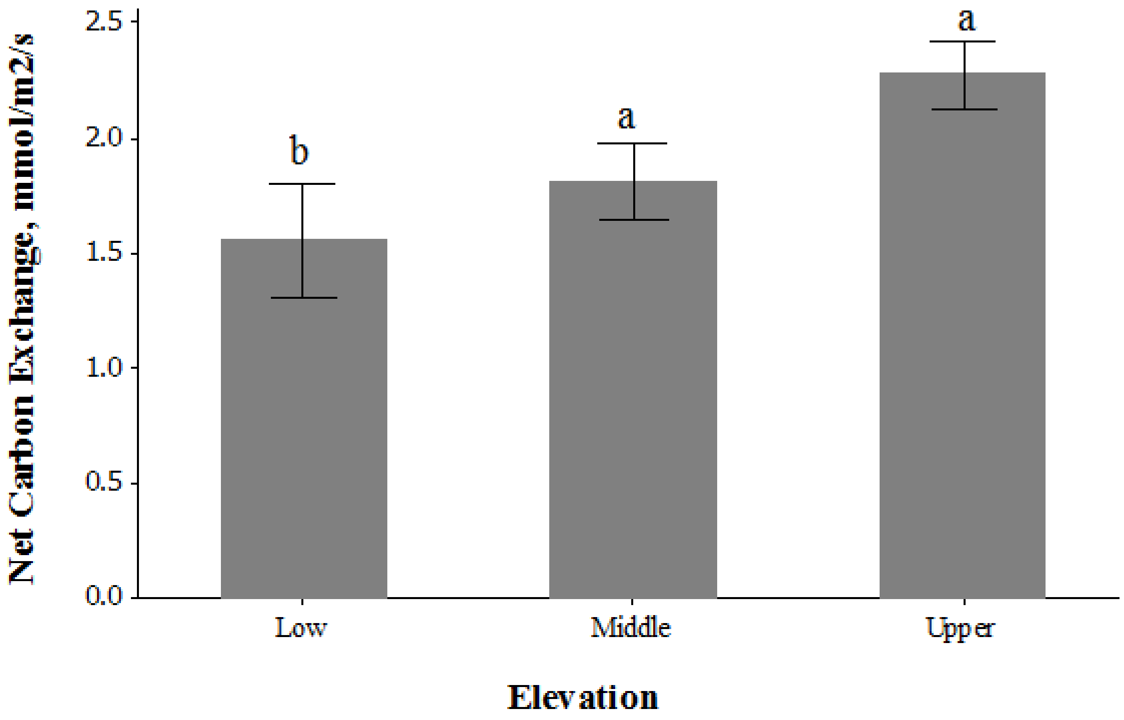


Figure 2.8. Net Carbon Exchange of three grassland types along in Lac du Bois Provincial Park. Error bars indicate ±SD. Bars sharing the same letters were not significantly different according to Tukey post-hoc test.

NCE showed significant influence of watering treatments in June and August (Table 2.3). Ecosystem respiration rates were significantly different in June and August for all treatments, except weekly spring and fall water additions and controls (Fig.2.9.) These treatments did not show significant difference in the means according to Tukey post-hoc test. In June, plots with monthly spring and fall water addition showed higher respiration rates than in August. Monthly fall waterings decreased June NCE rates in comparison with both spring treatments and fall weekly waterings. Following June’s trends, in August monthly fall waterings showed low and weekly spring waterings high NCE rates (Fig.2.9.). Respiration rates of fall weekly waterings in August were not statistically different from those of June.

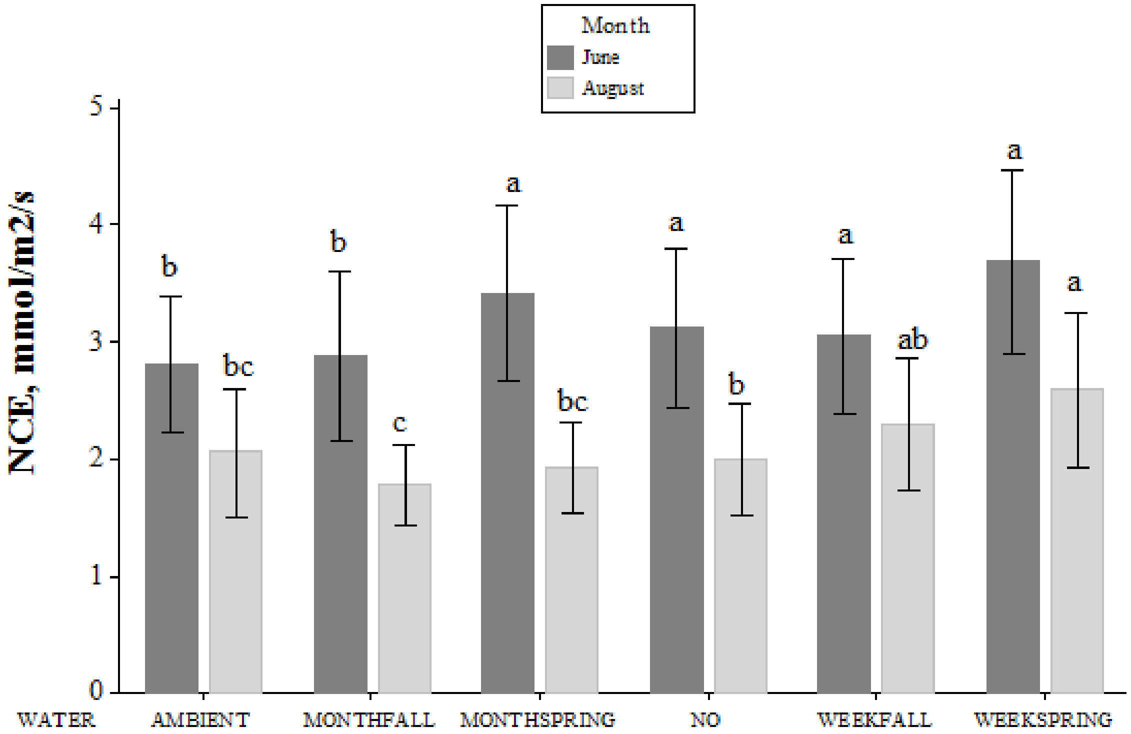


Figure 2.9. Net Carbon Exchange values of different watering treatments in June and August 2011. On the x-axis, ambient is the control, ‘MONTH’ refers to watering once a month, ‘WEEK’ refers to watering once per week, ‘FALL’ refers to watering in September and October, ‘SPRING’ refers to watering in May and June, and ‘NO’ refers to plots with false (control) rain-out shelters in Fall and Spring but with no watering. Error bars indicate ± SD. Bars sharing the same letters were not significantly different according to Tukey post-hoc analysis.

Net carbon exchange values of watering treatments were significantly different between elevations in August (Fig.2.10). Within elevation variation between rates corresponding to watering treatments was not significant for middle and lower grasslands. No significant difference was recorded for the same treatments between low and middle elevation (Fig.2.10). Weekly treatments of both seasons had an effect on upper grasslands respiration rates (Fig.2.10). Upper grasslands showed higher respiration rates under spring weekly and lower under fall monthly treatments. Monthly spring and weekly fall watering showed NCE rates that were not statistically different from controls.

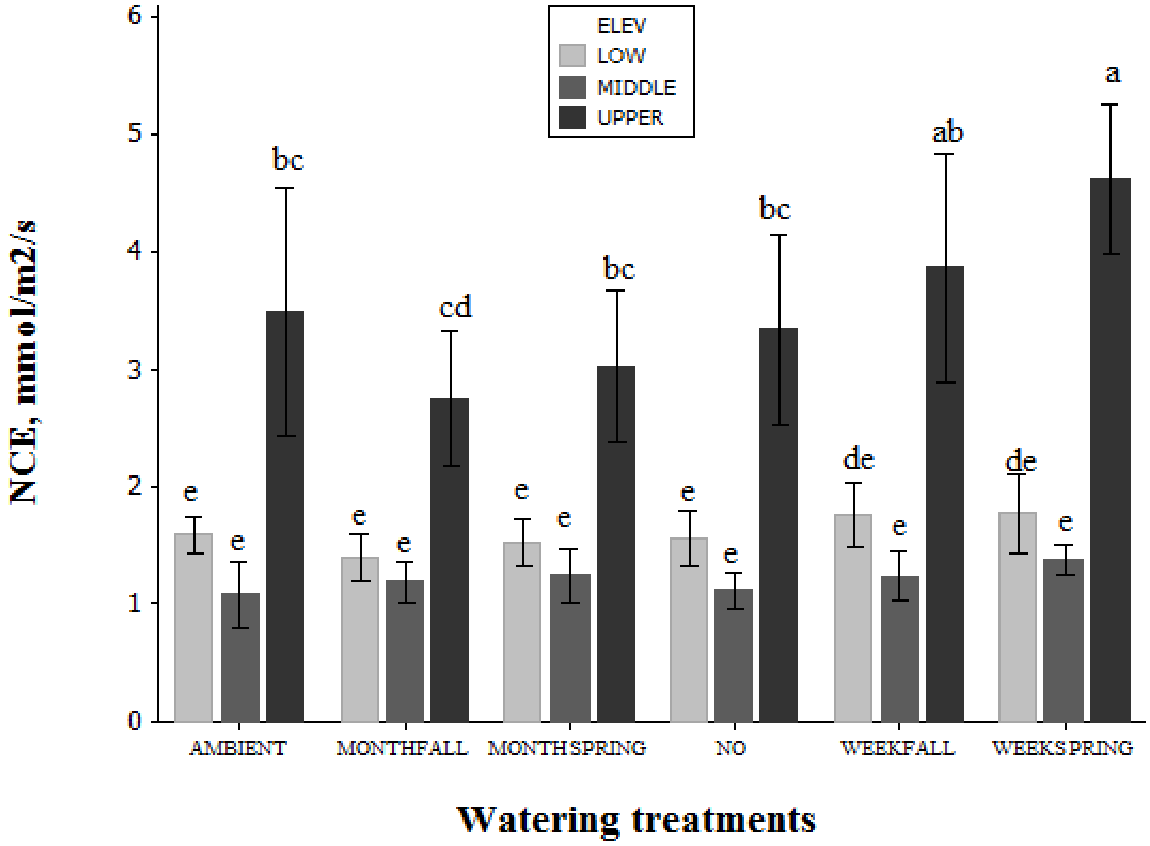


Figure 2.10. Interaction between elevation and watering on Net Carbon Exchange in August 2011. On the x-axis, ambient is the control, ‘MONTH’ refers to watering once a month, ‘WEEK’ refers to watering once per week, ‘FALL’ refers to watering in September and October, ‘SPRING’ refers to watering in May and June, and ‘NO’ refers to plots with false (control) rain-out shelters in Fall and Spring but with no watering. Error bars represent ±SD. Bars sharing the same letters were not significantly different according to Tukey post-hoc test.

Measurements during fall months (September, October and November) did not show significant effects of treatments on net carbon exchange (Table 2.3.). There was a change of NCE rates with elevation corresponding to the time of measurement (Fig.2.11). NCE rates decreased from September to November for upper grasslands. At lower grasslands there was an increase of NCE in November if compared to October, the rates of September and October were not significantly different. Middle elevation NCE rates did not change significantly with time. Respiration rates in November were not significantly different for lower and upper elevations and in September and October for low and middle.

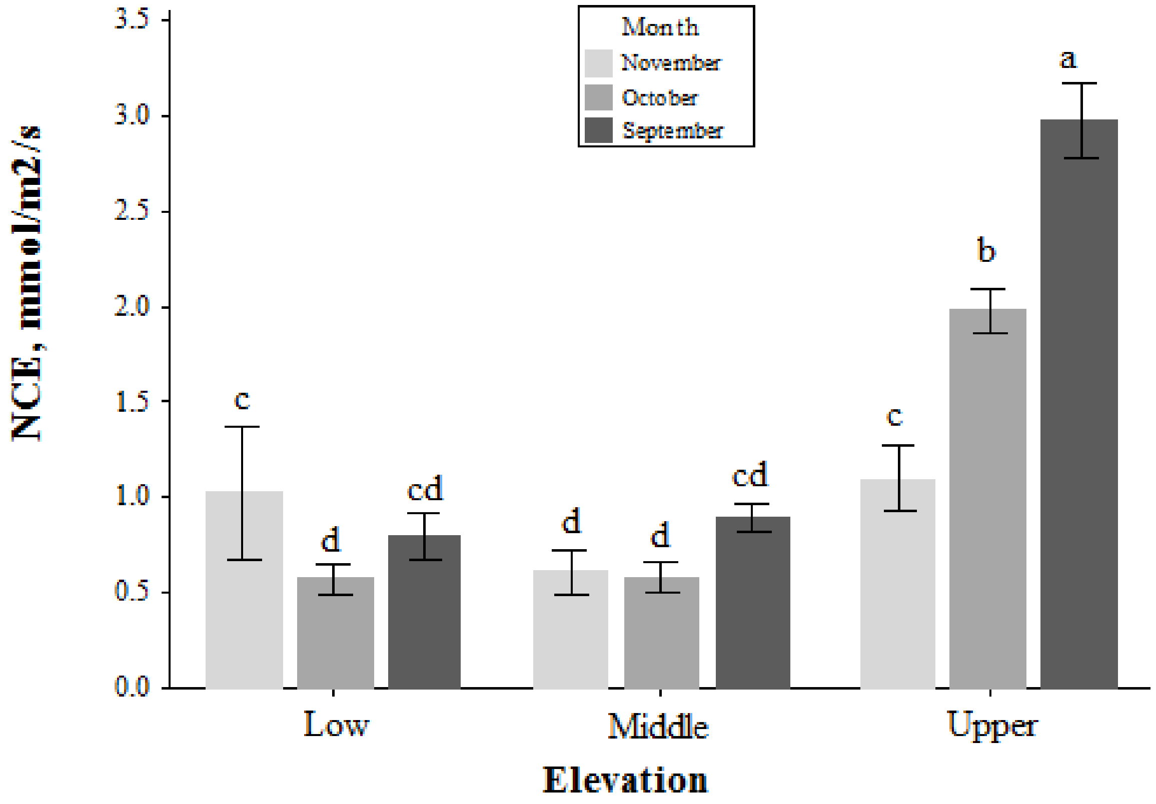


Figure 2.11. Net Carbon Exchange values at three grassland types by elevation (Low, Middle, Upper) over three time periods (September, October and November 2011). Error bars represent ±SD. Bars sharing the same letters were not significantly different according to Tukey post-hoc test.

Throughout the growing season ecosystem respiration rates increased from May to June, with peaks of NCE in June, and were consequently decreasing from August to November, with the lowest NCE in November (Fig.2.12.). Respiration rates of November were not significantly different from respiration rates of October.

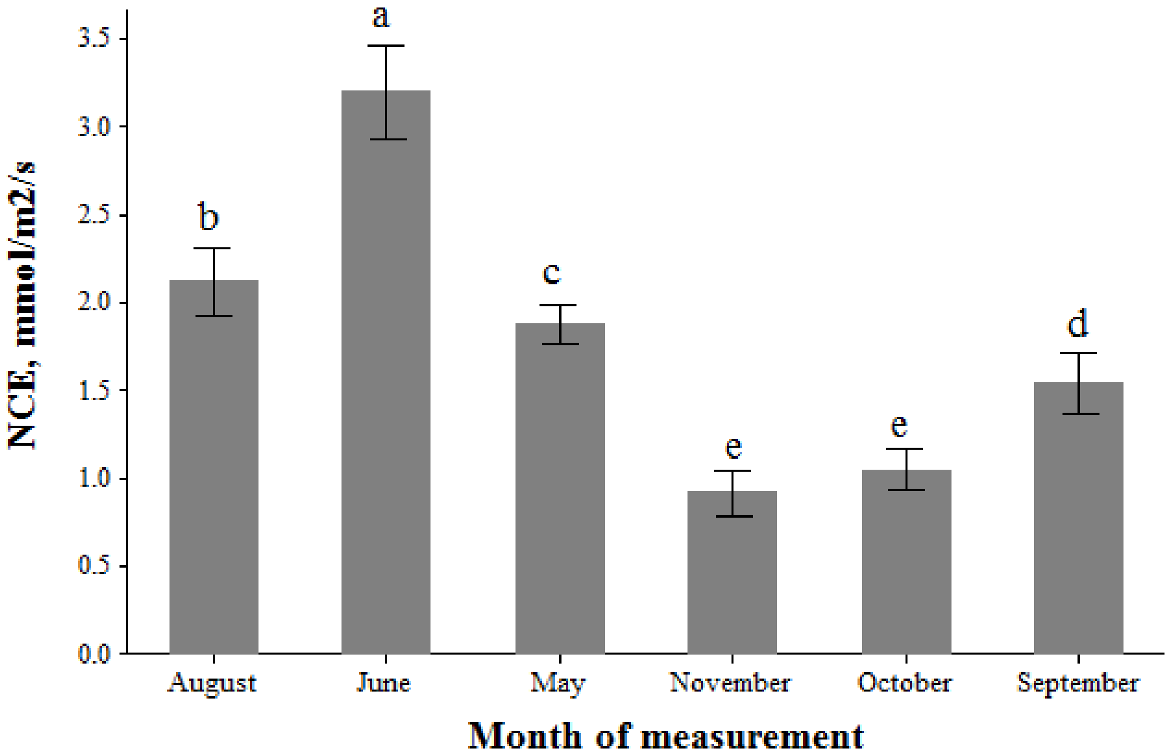


Figure 2.12. Change of Net Carbon Exchange values throughout the 2011 field season. Error bars represent ±SD. Bars sharing the same letters were not significantly different according to Tukey post-hoc test.

2.3.3 Carbon Dynamics of Spring vs. Fall Grazed Pastures

2.3.3.1 Carbon Pool of Soil

Soil carbon content of fall-grazed pastures was considerably higher than carbon content of spring grazed pastures according to 1-way ANOVA (F-ratio 4.895; P-value 0.034) (Fig. 2.13).

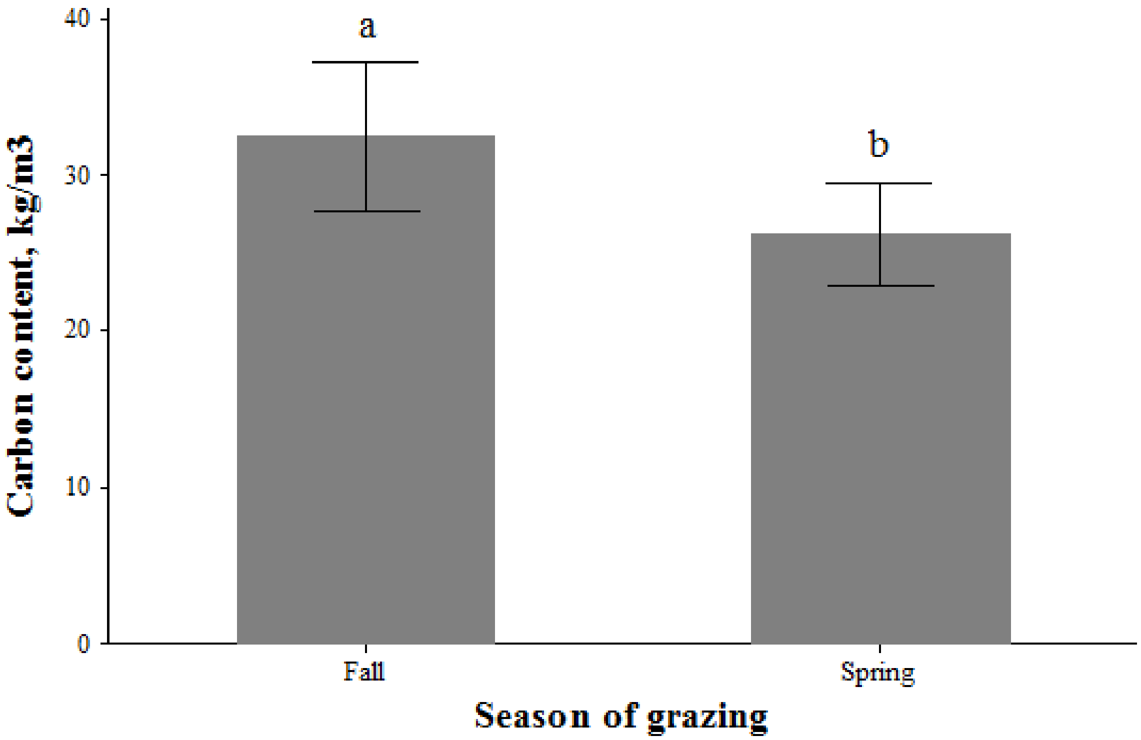


Figure 2.13. Carbon content of soils at 0-15 cm depth for fall and spring grazed pastures. Error indicates ±SD. The same letters indicate insignificant results according to Tukey post-hoc test.

2.3.3.2 Net Carbon Exchange (NCE)

Ecosystem respiration rates were higher at spring grazed pastures than at fall grazed pastures (F-ratio 8.946; P-value 0.006) (Fig. 2.14).

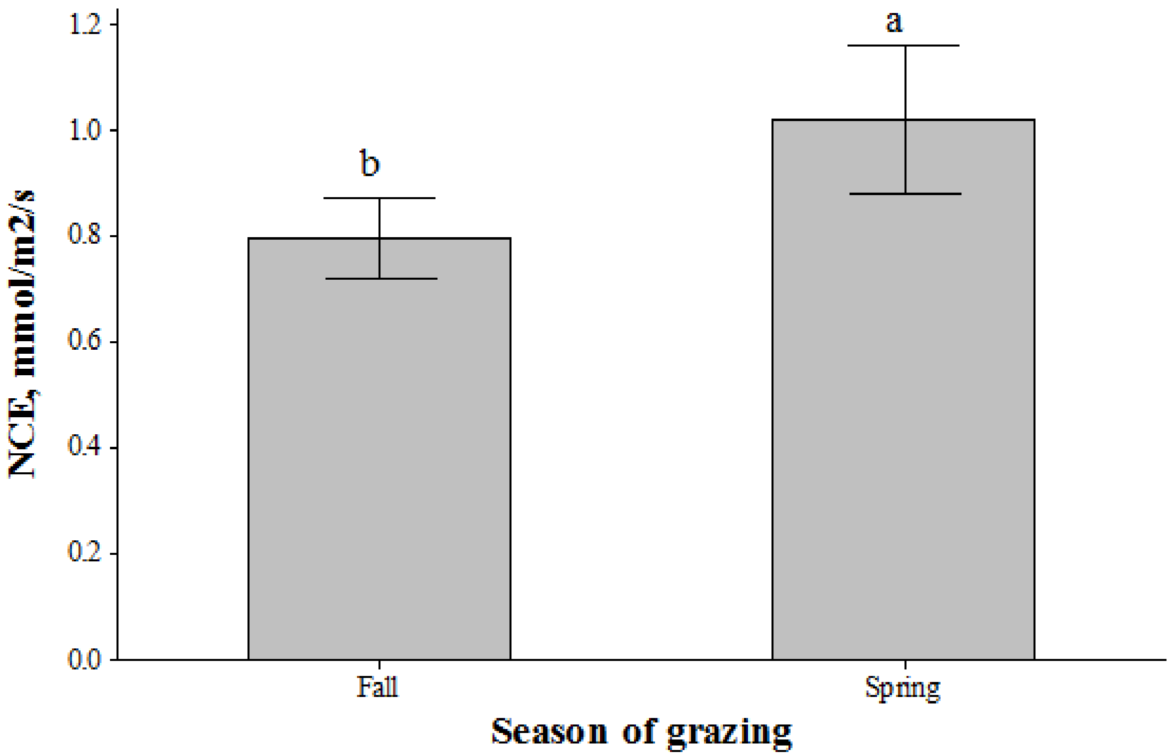


Figure 2.14. Net carbon exchange values at fall and spring grazed pastures. Error bar indicate ±SD. The same letters represent insignificant results according to Tukey post-hoc test.

2.4. Discussion

Soil carbon pools was greatest at the upper elevation grassland sites, which supports my first hypothesis. Soil carbon pools have been linked with primary productivity. Different grassland types showed different capacity for carbon storage in China (Ni 2001). Alpine meadows, high productivity ecosystems, dominated by fescue and Kentucky bluegrass, contained 25.6 % of China's total grassland carbon compared to 14.5% in alpine steppes (dominated by blue bunch wheatgrass), and 11% in temperate steppes (Ni 2001). Grasslands of the southern interior of British Columbia could also be divided into meadows, alpine steppes and temperate steppes (Tisdale 1947). This classification corresponds to elevation differences in grasslands communities. Upper elevation grasslands in the southern interior of British Columbia (meadows) have higher plant productivity and richness than low (temperate steppes) and middle grasslands (alpine steppes) (Tisdale 1947; van Ryswyk et al. 1966). Work is still needed to determine the mechanism of carbon sequestration by grasslands (Rustud 2006) and many factors need to be considered (Shulze 2006). De Deyn et al. (2008)

suggests that plant functional traits are major factors that will affect carbon storage of soils. They define a number of traits that could be related to accumulation and loss of carbon from the soil. The input is linked to plant primary productivity (relative growth rate) of above and below ground biomass, and output is connected to respiration, volatilization of organic compounds and leaching (De Deyn 2008). Relative growth rate as a main factor contributing to the carbon input is dependent on environmental factors, available nutrients and presence of herbivores (Tjoelker et al. 2005, Bardgett and Wardle 2003). As reported by Lee (2011), Lac du Bois grassland plant communities were varied and their differences depended on environmental factors and soil nutrient content, which was related to elevation, slope and aspect. Upper elevation and north facing grasslands had higher moisture availability and higher N and P content (Lee 2011). These results correspond with plant richness and productivity of upper elevation grasslands (van Ryswyk 1962), which support the idea that higher productivity grasslands are found in upper elevation sites and are better able to store carbon in soils than lower elevation and south facing grasslands.

A decrease in soil water availability did not show any influence on carbon load of soils. But fall increase in frequency of precipitation events led to corresponding increase in carbon levels. Flanagan et al. (2002) found that the amount of water available in northern temperate grasslands in southern Alberta, Canada was the driving factor for carbon gain and was positively correlated with Leaf Area Index and canopy nitrogen content. The response on the plant community and at the individual plant level might explain that process. Research conducted by Shinoda et al. (2010) in the Mongolian steppe showed the mechanism of plant response to the decrease in water availability. In a one-season experiment, the conditions of drought were experimentally created during the growing season and above and below ground plant biomass was evaluated. They report that below ground plant biomass was not affected by water decrease, but that above ground biomass decreased considerably (Shinoda et al. 2010). However, a decrease in productivity due to dry conditions has been linked with loss of plant diversity by De Boeck et al. (2006). Catovsky et al. (2002) confirms that loss in biodiversity may result in change of quantity and quality of litter and respiration and decomposition rates, which in turn leads to change in primary production. As mentioned before, plants also are accountable for loss of carbon as well, and respiration plays an important role in the process (De Deyn et al. 2008, Zhou et al. 2007, Huxman et al. 2004).

Net ecosystem exchange (NEE) rates may vary during the season and are highly dependent on moisture availability (Potts et al. 2006). The results of my study showed that the highest levels of NEE occurred as a result of spring water addition, which led to a decrease in carbon content of soil. These results are opposite to the findings of Potts et al. (2006), which reports the constraining effect of spring watering “pulses” on ecosystem respiration rates. Other researchers, Huxmen et al. (2004) and Zhou et al. (2007), report that the size of precipitation events might be crucial in the balance between carbon uptake and carbon loss. Huxman et al. (2004) suggested that large precipitation pulses can enhance carbon sequestration by supporting plant functioning after the event.

My hypothesis regarding NCE decreasing due to clipping (a surrogate for grazing) was not supported. Net carbon exchange was not affected by the clipping treatments; although negative change in carbon content was detected after clipping treatments was applied. Zhou et al. (2007) reports similar findings in a six year experiment with yearly biomass removal. During the first four years there was no change in NCE rates, but years five and six showed a decrease in carbon efflux from the ecosystem. Wan and Lou (2003) showed a significant CO_2 efflux decrease in an experiment where clippings were done throughout the entire year. Thus, the NCE behavior might be dependent on the intensity of grazing and the period of time the disturbance is applied to the site. Although the carbon efflux in my experiment did not change due to the clipping treatments, negative change in carbon of clipped plots at the upper elevation might be explained by timing and intensity of clipping in the growing season. The plots were clipped at 5 cm stubble height, which represents intensive grazing. Padney and Singh (1992) investigated the above and below ground productivity of savannah under different grazing regimes and found that above ground productivity decreased with the increase in intensity of grazing. Significantly, light to moderate grazing was beneficial in terms of enhancing plant productivity. Below ground productivity decreased when grazing was applied with the lowest at high grazing rates. Considering the response of grasses to different grazing intensities, the decrease in carbon content of my study might be explained by a decrease in above and below ground plant productivity caused by a heavy clipping treatment, analogous to heavy grazing. Moderate levels of grazing (e.g., grazing to 15-20 cm above soil level) has been shown to enhance soil carbon storage (Franzleubbers 2010). In addition, upper plots were clipped in early July, which coincides with the peak of the growing season. Therefore plants would not have the maximum capacity to respond to clipping by increasing growth rate. Timing of clipping might be another reason why low and mid – elevation grasslands did not show any significant results. The timing of grazing is an important factor that should be considered for range management of soil carbon sequestration. Further work is needed to test different grazing intensities on the potential for soil carbon sequestration in rangelands.

The hypothesis of my second study was supported; fall grazing was the most favorable management practice for enhancing carbon sequestration in soil. More likely such results are explained by the activity of the plants in the beginning and the end of the growing season. In the spring, photosynthesis is active and plants are in their growing cycle when most of the produced carbon goes toward growth and increasing biomass. This and high respiration rates limits deposits of carbon in the soil. When grazing is applied early in the season, plants require time and resources to compensate for the loss of biomass, limiting carbon deposition into the soil. In contrast, fall grazing is on ‘hard” grassland plants that are fully grown and at the end of their growing cycle.

Carbon sequestration in grasslands is a complex process and many factors need to be considered, including the effects of climate change. It seems that management practices can influence soil carbon intake, but more research is needed on the effect of different grazing intensities during different times in the growing season on soil carbon sequestration. Plant responses to the disturbance on individual and community levels need to be considered when developing management regimes. The present study concludes fall-grazing of low and middle elevation pastures beneficial in terms of carbon storage and mid-season grazing of upper elevation grasslands has a negative effect on soil carbon.

Chapter 3. – Economic Assessment of Grassland Ecosystem Services and Development of Grassland Profit Potential model: the case of Lac Du Bois Grasslands

3.1 Introduction

Terrestrial ecosystems contain about 1500 Pg of carbon in the surface meter of soil and another 600 Pg in the vegetation (Batjes 1996), which is three times the amount of carbon in the atmosphere. Thus any changes in carbon storage of plants or soils should lead to significant implications for the atmospheric concentration of carbon dioxide (Shuman 2002). Rangelands (including grasslands, shrub lands, deserts and tundra) occupy about half of the world's land area and contain about a third of above and below ground carbon reserves (Allen-Diaz 1996). Changes in rangeland soil carbon can occur as a result of variety of management and environmental factors (Shuman et al. 2002). It is necessary to monitor and prevent practices which result in releasing carbon into the atmosphere and to develop new management practices that enhance carbon sequestration.

Grasslands play a significant environmental, social and economic role. Recent studies have shown the importance of grasslands for climate change mitigation (Scurlock and Hall 1998; Frank 2002; Rees 2005). Grasslands can provide a considerable "carbon sink" for atmospheric carbon, and therefore decrease carbon dioxide levels in the atmosphere. The process that drives grassland carbon sequestration is the carbon cycle. Net primary productivity of grasslands is linked to the potential for carbon storage, but unlike the "forest carbon sink", where most of the carbon stored is in the above-ground biomass, carbon storage in grasslands will mostly occur in the soil and below-ground biomass (Scurlock and Hall 1998). Plant biomass is a way to transfer atmospheric carbon into soils. Carbon in the soil is transformed into stable forms and remains there for a long time. The carbon content of grasslands has been estimated at 200 – 300 tC/ha (Sousanna 2004). What is not known is how management can influence grassland carbon storage and the maximum potential for carbon storage in grassland soils.

Temperate grasslands of the southern interior of British Columbia occupy less than one percent of the province. Despite the small territory, B.C.'s grasslands provide home for a large proportion of species at risk in B.C. Grasslands of British Columbia are the main source of forage (Wilson 2009). Grasslands are a key subset of BC's rangelands. Rangelands, especially grasslands, are threatened by urban development, agricultural conversion, tree encroachment and infill and inappropriate grazing. Global climate change has the potential to interact with the above disturbances, but the consequences of these interactions for rangelands in B.C. are not known.

Despite the importance of grasslands for providing ecosystem services, they continue to be destroyed. Every year about 12 million hectares worldwide are lost to land degradation, and the rate is increasing (IFAD 2009). Part of the problem is the lack of scientific data about grasslands degradation and its influence on people and environmental stability. Another problem is the absence of adequate and effective policies, which account not only for marketable services but includes the non-marketable value of grasslands, such as carbon sequestration. Today, policymakers are trying to develop the marketable value of "carbon sinks" by means of carbon banking and trading. For this purpose data about possible "carbon sinks" are required. Efforts to evaluate the significance of forests for providing ecosystem service of carbon sequestration have been made (Deveny 2009; Seidl and Moraes 2000). Unlike forest carbon sinks, grasslands ability to store carbon is poorly understood.

The framework for economic evaluation of ecosystem services was developed by Costanza et al. (1997). The authors suggested that valuing services is "determining the differences that relatively small changes in these services make to human welfare" (Costanza et al. 1997). Cost estimates are usually based on a "willingness to pay" for those ecosystem services by their users (Costanza et al. 1997). However, not many people are aware of the services that ecosystem could provide, which can lead to uncertainties in cost estimates. Scientific data about effects of climate change and management practices on certain ecosystems is limited (Chee 2004).

The goal of this study is to explore the economic evaluation of grassland ecosystem services for temperate grasslands of the southern interior of British Columbia. The assumption I make is that carbon sequestration by grasslands is the service that can provide monetary value. The Grassland Carbon Profit framework (GCPF) model has been designed to represent this value (based on Deveny et al. 2009). Carbon Profit Value (CPV) reflects the profit potential that a given location could provide. CPV depends on economic and biological variables. Economic factors include the price of carbon, opportunity cost of the land and discounting rate. An important component of ecosystem services assessment is discounting (Bateman et al. 2010). The value of each good is assessed as the discounted present value of the stream of net benefits which are expected to be received into the future. Reasonable assumptions were made about economic variables and sensitivity analysis provided insights to the possible outcomes in the future. The biological factor is the quantity of grassland carbon. Although economic factors of the index are uncontrollable and depend on the current political and economic situation in the world, quantity of grassland carbon can be controlled. Understanding the dynamics of grassland carbon is important. The field experiment was designed to study soil carbon pools and the dynamics of carbon exchange in three different grassland types that vary in site productivity, and how different precipitation patterns may influence carbon storage.

The rest of the paper proceeds as follows. Section 3.2 describes the Grassland Carbon Profit framework. Section 3.3 describes the biology part of the framework. In order to represent the changes of carbon content under different climate and management scenarios the field experiment was designed. It is described in section 3.3.1. Section 3.4 explains the three economic variables. Section 3.4 describes the grassland profit potential model. Section 3.5 presents the findings of the field experiment and describe how those findings altered the economic variable of the model. Section 3.6 presents the results then followed by a discussion.

3.2 Method – Grasslands Carbon Profit Potential Framework

The grassland carbon profitability framework gives us the possibility to compare the ability of different locations within country (and between countries if applicable) to generate grassland carbon credits. This ability is based on two factors – economic and biological (Figure 3.1). The GCPP framework captures each of these factors, which reflects the full set of conditions that influences grassland carbon generation (Deveny et al. 2009)

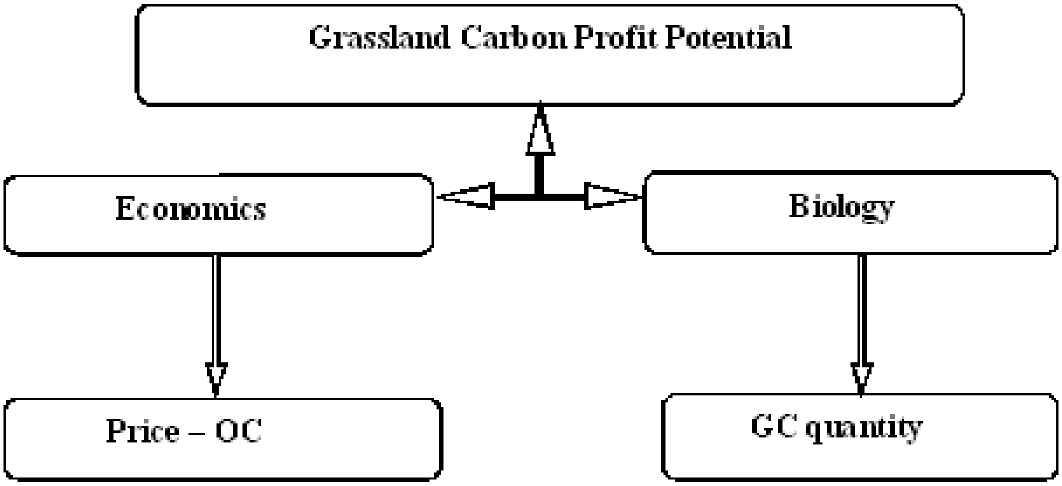


Figure 3.1. Grassland Carbon Profit Potential Framework. Price is referred to the current price of carbon (per tCO_2eq); OC – opportunity costs of the land ($ per ha); GC quantity – quantity of grassland carbon (tCO_2eq per ha).

Profit potential describes the ability of a given location to generate abundant and low-cost grassland carbon, based on economics and the biology of the location. Profit potential incorporates the amount of carbon credits that could be created at the certain location. It represents the net profit (in dollars) that could be obtained by selling all the potential grassland carbon.The profit potential is calculated as follows:

$$PP = (P - OC) * GC \tag{1}$$

-where PP is profit potential, P is price of carbon per ton, OC is the opportunity cost of carbon sequestration per ton, and GC is quantity of carbon credits.

Profit potential depends on the profit margin, price less opportunity cost of having grasslands as storage of carbon multiplied by the quantity of carbon stored underground. The next section expands on the biology and describes the field experiments conducted to measure the quantity of grassland carbon.

3.3. Biology

3.3.1 Quantity Model for Grasslands Carbon

Quantity of grassland carbon credits depends on the biological potential of the given location. Biological potential of the land to produce grassland carbon is estimated as an amount of tons of carbon per hectare that would accumulate within the period of time (the period to reach a carbon sequestration target is the subject for further research). The amount of carbon credits are represented in tons of CO_2 equivalents per hectare.

The grassland carbon (GC) quantity model can be computed as follows:

$$\text{GC Quantity} = \left(\frac{tCO_2eq}{ha} \bigg|_G \right) = \left(\frac{tC_{yearX}}{ha} \bigg|_G \right) \cdot \left(3{,}66 \cdot \frac{CO_2eq}{C} \right) \tag{2}$$

where the $\left(\frac{tC_{yearX}}{ha} \bigg|_G \right)$ - is amount of carbon stored within a period of *X* years per hectare of the land; and $(3{,}66)$ - is the conversion factor, converting carbon into CO_2 equivalent.

In order to estimate current carbon quantity and its potential variation under climate change and management scenarios field experiment have been designed, that is described further.

3.3.2. Field experiment

The duration of the experiment was two growing seasons starting in May 2009 and finishing in November 2011.

The study was designed as a part of a larger experiment aimed to test how controlled precipitation manipulations and clipping affect the plant community and soil properties of the different grassland types in Lac du Bois. The design altered precipitation timing and frequency. Twelve different treatments (1 block) were selected to represent potential climate change and grazing scenarios. Each treatment was replicated 6 times. Amount of water added to the plots were calculated on the base of monthly averages for the last thirty years, plus fifty percent increase to compensate for the rain shading effect of the shelters and increase in fall-winter precipitation according to the climate change models for BC (Loukas et al. 2001).

Twelve treatments were implemented: 1) control plot, no treatment was applied to this plot (AMBIENT); 2) clipping control plot, only clipping treatment was applied (CLIP); 3) rain shade control plot, shredded rain shades were installed to determine if rain shades have influence on the environmental factors (soil moisture and temperature) (NO); 4) rain shade plus clipping control, to determine if interaction of two factors affects soil moisture and temperature (NO + CLIP); 5) Spring water addition on a weekly basis (WEEKSPRING); 6) Spring water addition on a weekly basis plus clipping (WEEKSPRING + CLIP); 7) Spring water addition on a monthly basis (MONTHSPRING); 8) Spring water addition on a monthly basis plus clipping (MONTHSPRING + CLIP); 9) Fall water addition on a weekly basis (WEEKFALL); 10) Fall water addition on a weekly basis plus clipping (WEEKFALL + CLIP); 11) Fall water addition on a monthly basis (MONTHFALL); 12) Fall water addition on a monthly basis plus clipping (MONTHFALL + CLIP). All plots, except one and two (control and clipping control), had rain shades installed during watering periods, to block natural precipitation (Table 3.1).

Table 3.1. Experimental design of the study

Plot #	**Watering treatments**				**Rain shades**		**Clipping**
	Spring		**Fall**				
1	-	-	-	-	-	-	-
2	-	-	-	-	-	-	Yes
3	-	-	-	-	**Spring**	**Fall**	
4	-	-	-	-			Yes
5	Weekly	-	-	-			
6	Weekly	-	-	-			Yes
7	-	Monthly	-	-			
8	-	Monthly	-	-			Yes
9	-	-	Weekly	-			
10	-	-	Weekly	-			Yes
11	-	-	-	Monthly			
12	-	-	-	Monthly			Yes

Clipping manipulations represented disturbance to the plant communities that usually occurs on the rangelands in the form of grazing. The clipping of plots was done in the middle of the growing season between late June and early July. Vegetation was clipped to a height of 5 cm. This height of clipping represents a typical post-grazed stubble height in heavily grazed rangelands (Ministry of Agriculture, Food and Fisheries 2005).

Soil samples were collected from each experimental plot at two depths, 0-15 cm and 15-30 cm, using a soil corer with a 2 cm diameter and 30 cm length. Due to the shallow depth of soils at the middle grassland site, I was not able to sample the 15-30 cm depth of middle grasslands. Soil cores were stored in zip-lock bags and transported to the laboratory where they were air dried. Dry soil samples were sieved with 2mm mesh to separate coarse fragments, roots and small rocks.

3.4. Economy

3.4.1. Opportunity Costs of Land

The cost of grassland carbon at any given location depends not only on the quantities of credits that can be sold from a given location, but also on the cost of land known as the opportunity cost. The opportunity cost of land plays a critical role in determining the cost of generating grassland carbon credits. Opportunity cost reflects the value of the next best alternative the land can be used. It represents the value of that land by estimating how much revenue the next highest-valued use could generate. For example, grasslands are often converted into croplands or pastures. The opportunity cost reflects the value generated from croplands or pastures. The focus of this paper is on grasslands that are used or could be used as grazing lands for cattle.

Opportunity cost is composed of private costs and/or net social benefits associated with the alternative. The private opportunity costs of land are the largest cost associated with using grasslands for carbon sequestration. It is assumed that all the foregone revenue into the future from grass-fed cattle industry represent the total value of the land or the cost of purchasing the land. A generalized model that calculates the present value of foregone rents over the next 100 years is used to calculate the opportunity costs of the land.

The private opportunity costs of carbon sequestration by grasslands are the rental value of land (in dollars per hectare) divided by the quantity of grassland carbon that can be generated from that land (in tons of CO_2eq per hectare). The cost of carbon sequestration is determined by the biology of the land and the effect of future climate change. This represents the cost of individual credit in dollars per ton of CO_2eq.

It is assumed that the opportunity costs (OC) of generating the grassland carbon are the present value of foregone rents from grass-fed cattle (GFC) industry over the next 100 years:

$$OC_p = \left(\left. \frac{\$}{tCO_2eq} \right|_G \right) = \sum_{t=1}^{100} \frac{\$GFC/ha}{(1+r)^t} \cdot \frac{1}{\left. \frac{tC_{yearX}}{ha} \right|_G 3{,}66 \cdot \frac{CO_2eq}{C}}, \qquad (3)$$

Where \$GFC/ha is the annual rangeland rent per hectare, t – is the numbers of years, and r – is the discount rate in terms of time reference for a land owner in valuing the land over the certain period of time.

The private opportunity cost of grasslands for carbon sequestration above ignores any other social benefits or costs that can arise from the alternative. A proper profit or cost benefit analysis should account for these additional costs. Thus the primary assumption about the opportunity cost above is correct as long as the alternative (i.e., cattle grazing) provides no additional social benefits or costs from the activity. But many studies exploring the connection of grazing to carbon sequestration discovered that grazing may result in additional carbon storage (Shuman et al. 1999; Derner 1997). In this case, we will have an additional benefit of carbon sequestration with grazing. Because carbon sequestration is considered as an environmental service and has a value for society, grazing will be considered as a social benefit (SB). But grazing provides not only social benefits, but might result in social costs (SC). These social costs might be associated with overgrazing, soil disturbance, methane emissions and water contamination. Hence the overall opportunity cost of maintaining grasslands for carbon sequestration is:

$$OC_s = OC_p + SB - SC \tag{4}$$

Thus the opportunity cost of keeping grasslands pristine (OC_S) for carbon sequestration is higher (i.e., receives a lower profitability value and hence might be converted to grazing) the higher the social benefits which might be associated with cattle adding to the carbon sequestration of the land and the lower the social costs of grazing. Only when these additional elements, of the opportunity cost, are accounted for can a proper profit potential be developed to evaluate grasslands.

3.4.2. Carbon Market and Carbon Price

Anthropogenic GHGs emissions are the main cause of the recent and predicted future climate change (Hansen et al. 2006). As GHGs exist in the atmosphere as a part of carbon cycle, its amount is increasing rapidly due to human activities. Human activity includes energy production, industrial development, transportation and land use (Stern 2006). As a subject of economic analysis human-induced climate change could be viewed as a negative externality. A negative externality is the external cost inflicted on people which is not transmitted through prices. Those who produce emissions, thereby bringing climate change, they impose costs on society and future generations. At the same time the producers do not pay for these costs neither through markets, nor in other ways. The effect of their emissions is unpredictable and possibly distant, in time and space. As emissions don’t cause immediate damage, there are few economic incentives for people to reduce them. There is no reason for people to compensate those who lose because of climate change, unless policy regulations are applied. Mitigating the effects of climate change is also a public good. People who don’t pay for it couldn’t be denied the right of using it. They basically want a free ride on the backs of others that take action. It is an intra-generational (within generations) as well an intergenerational (between generations) problem. Intra-generational issue refers to the issue that the least contributors to the problem will be the ones that are most affected by climate change (e.g. Africa). Intergenerational in that the future unborn generations will suffer the most from climate change relative to the present. Uncertainty is not well understood and is considered enormous with the possibility of extreme damages happening (Weitzman 2012). Thus anthropogenic influence on climate represents the world’s biggest market failure (Stern 2006).

Nowadays, carbon regulation is based on carbon taxes. For example, Denmark and Finland have imposed such taxes. Under the carbon tax system the government sets the price of carbon and reduction is determined by every emitter. The incentive to reduce emissions arises if the marginal abatement costs are lower than the tax payments to the government. Given that marginal abatement costs are low initially tax savings from reducing emissions exceeds the marginal abatement costs making it attractive to firms to reduce emissions.

However effectiveness of carbon taxes is debatable. Keohane (2009), in his paper “Cap and trade, Rehabilitated”, talks about differences between cap and trade (marketable permits) and carbon taxes. He says that system of tradable permits is more flexible in allocating the value of emissions and more politically feasible. Trading promotes cost effectiveness, broad participation and equity in the international context, without high level coordination that a tax would require (Keohane 2009). Metcalf (2009) in his article “Carbon tax to reduce U.S. greenhouse gas emissions” is defending carbon taxes as an important way of regulating greenhouse gas emissions. First he states, that setting the one price for emissions provides the incentive for producers to begin emission reduction through changes in process and investments. Second, a commitment to recycle the carbon tax revenue to low income groups could create a political discipline. And finally, carbon taxes could be imposed more rapidly, than cap and trade system.

Despite a common view of economists on mitigating the effects of climate change as a market failure, policymakers in cooperation with economists and industries are attempting to create a stable and functioning carbon market (Wilson 2009). Carbon market is referred as an important economic institution as a regulator of greenhouse gas emissions and plays an important role in complementary ecological processes. A grassland carbon market cannot exist by itself and can be developed only as a part of global carbon market. Carbon markets are designed to internalize the externality by creating a market to trade emissions. Buyers and the sellers of GHGs reductions benefit from such a market. Permits to pollute are issued by the regulatory authority. Through trade a market price is established. The market price is determined by supply and demand for carbon permits. Supply of carbon permits is determined by the marginal abatement cost curve. This curve shows the additional cost of reducing GHGs emission by 1 tonne. A marginal carbon abatement cost model for the global carbon market has been developed by McKinsey and Company (2009) (Fig.3.2).

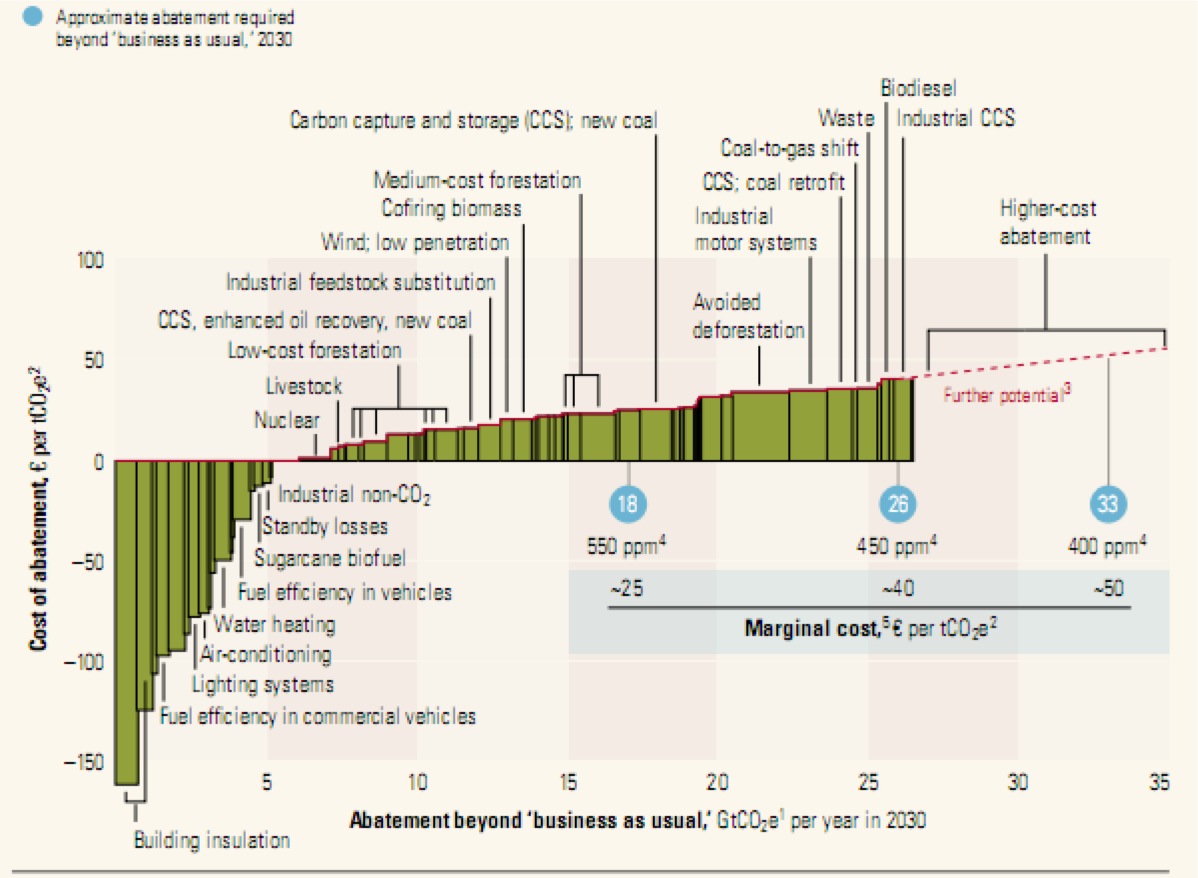
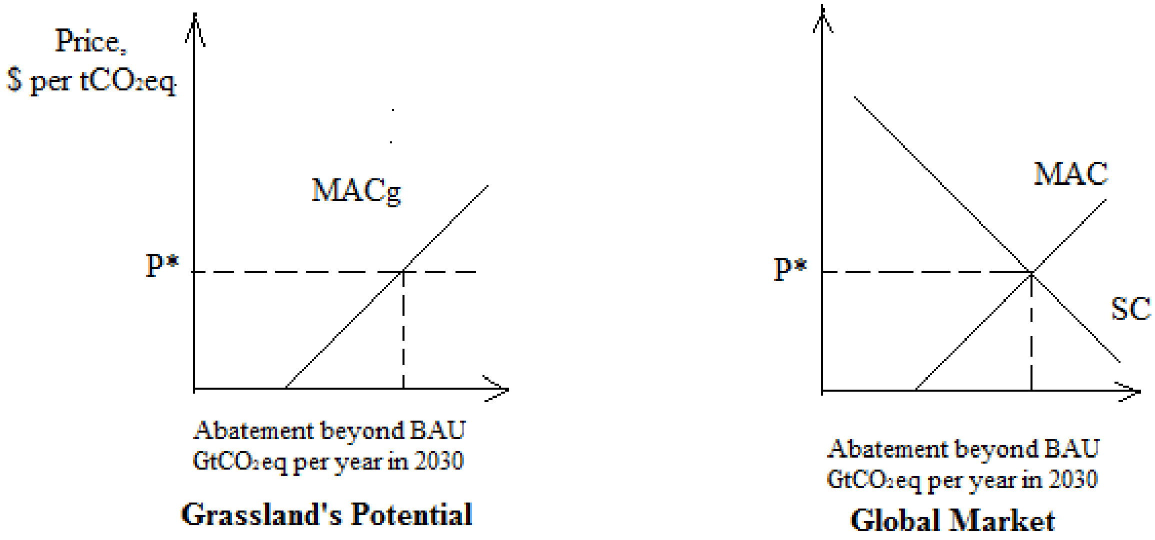


Figure 3.2. Global cost curve for greenhouse gas abatement (McKinsey and Company 2009)

Here the "supply" of abatement is compared with "politically" determined target for abatement in years 2010, 2020, 2030. The target for abatement is the three emissions levels that would cap the long term concentration of greenhouse gases in the atmosphere at 550, 450 and 400 ppm, which in temperature equivalent will be in the range of 2-3° Celsius increase. This curve shows the estimated costs of feasible abatement measures in 2030. At the low end of the curve are measures that improve energy efficiency. Higher up the cost curve are approaches for adopting more GHG-efficient technologies (wind power and industrial carbon capture and storage) (McKinsey and Company 2009). Abatement costs will vary by countries and by industries, but to be effective, in meeting the target of 450 ppm, the price of carbon should be approximately 40 Euros per tonne in 2030.

Although Grassland carbon has not been included into this abatement cost curve, we will assume that the nature of the carbon storage process allows us to include it in a category of a natural CCS (carbon capture and storage). In the later part of this chapter we will provide estimates of the cost of abatement of carbon by grasslands using the concept of opportunity cost.

For now we will assume that the marginal abatement cost curve for grassland carbon can be seen to be part of the global market as shown in Figure 3.3.



Grassland's Potential

Global Market

Figure 3.3. Carbon market potential. Abbreviation BAU refers to business as usual. MAC is marginal abatement curve, and SC is a social cost curve.

The right hand side of figure 3.3 shows the global market for carbon sequestration. The MSC is a marginal social cost curve. It represents society’s willingness to pay to abate one extra unit of GHGs. At low levels of abatement the marginal social costs are high, implying that society is willing to pay a lot to reduce GHG emissions by 1 tonne. This willingness to pay drops as abatement increases. Thus the MSC slopes downwards with increasing abatement. The MAC is a marginal abatement cost curve. The MAC slopes upwards according to the chosen scenario. Abatement costs increase with increasing abatement. The more stringent the target/scenario by 2030 the more steep is the MAC curve. The optimum level of abatement and price of carbon is determined at the intersection of MAC and MSC.

The left hand side of the figure shows the supply curve or the marginal abatement cost curve for using grasslands. It is labelled MAC_G and is a small component of the overall MAC. The supply curve represents the opportunity costs of carbon sequestration with grasslands. Opportunity costs are the value of the next highest-value use of this land, which have been sacrificed to achieve carbon sequestration target. For example, the opportunity costs of maintaining natural grasslands will be the revenue which can be gained by using this land for agriculture or cattle production. So the total costs of the land (and therefore abatement) will be a sum of all foregone revenues from alternative use of this land.

The demand for grassland carbon which is part of the overall demand for carbon sequestration will be represented by maximum willingness to pay to sequester carbon. Maximum willingness to pay will be either willingness to pay to preserve natural grasslands from development and conversion, or willingness to pay to create emission offsets through improved management practices. In first case the demand will be created mostly by society, in second case it will be carbon emissions producers such as fossil fuels production industries, cement production and industries that use fossil fuels in big volumes for their production processes.

Carbon price emerges from the emission trading schemes and plays an important role in regulating carbon market. The main determinants of carbon price are 1) policy and regulations and 2) market fundamentals (Cararro and Favero 2009). There are two ways the price of carbon is determined. First, the market could determine the price via a cap-and-trade system. Secondly, the government can set the tax on carbon emissions.

In cap and trade system the government places the cap on the emissions and allocates the allowances between emitters. Emitters are free to trade among each other to meet the target. Firms that have clean technologies will find themselves with an abundance of allowance, while firms that have older dirtier technologies will demand more allowances. Many buyers and sellers of allowances will find it beneficial to exchange allowances at a price determined by the market forces. As a result of trading would continue until the carbon price reflects the value placed by the last marginal user of the allowances. The market carbon price of emissions depends on the demand and supply of allowances (Cararro and Favero 2009).

The carbon price depends on the state of the economy as well as the amount of emission allowances available (Nordhaus 2007). Other important price determinants are climate conditions. In conditions of growing economy the implications are that emission levels will go up as well, that will lead to the higher demand on the reduction allowances and therefore increase their price. In changing climate (more hot summers and cold winters) more energy will be required that will lead to more emissions and as a result higher carbon prices (Bole 2009). Presently market factors, such as commodity prices (oil, gas, coal), play an important role in regulating carbon market. Carbon price depends on the type of fuel and the costs of switching from more emitting fuel (coal) to least emitting (gas) (Cararro and Favero 2009). Therefore the price of gas and coal will likely be important factor until carbon capture and sequestration projects becomes more available.

Although Kyoto protocol sets the standard and creates a large and well established carbon market, not all countries are a part of the agreement. Many countries create their own policies and carbon markets. This multitude of small markets makes it impossible to set a uniform carbon price. But as a largest and most stable market European Union Emission Trading Scheme sets a benchmark for carbon price. Currently theoretically estimated carbon price is 20$ per tCO_2 (den Elzen et. al. 2011). Tol (2008) conducted a meta-analysis of more than 200 studies that estimated social costs of climate change. He confirmed that the average social costs of carbon between 20-25 dollars per ton of carbon under 3% discount rate are justified.

From the grassland perspective, carbon credits will ultimately have to compete with credits generated from all other sectors of climate mitigation in the carbon markets. If offsets generated through energy efficiency projects or methane recapture projects are cheaper than grassland carbon offsets, these competing offsets will be preferred in the market. The purpose of the price constraint is to reflect that buyers of grassland carbon credits realistically have an entire credit market to choose from under a Cap-and-trade system. These buyers will always have the option to purchase the most affordable offsets on the international carbon markets, and if grassland carbon credits are too expensive, buyers will have the option of purchasing non-grasslands credits. The effect of the price constraint is that only the affordable grassland carbon credits are counted in the model as a part of the local supply, and the excessively expensive credits are excluded.

3.4.3. Discount rate

Climate change policy is closely based on estimations and predictions about the future consequences of changing climate. It is known that concentration of greenhouse gases

(GHG's) are the cause of increasing temperature on Earth which will lead to damages (IPCC 2007). Anthropogenic emissions of GHGs need to be reduced. Reductions in GHGs results in costly activity but has future benefits. Costs of reductions occur today, while benefits of action appear in the future (Arrow 2007). Future benefits are valued less today due to discounting. Alternatively the cost benefit study can be expressed in terms of the cost of inaction. Inaction will result in damages to future generations but lead to cost savings today. Do the benefits exceed the costs of action or inaction? A cost benefit analysis of action or inaction is required to make an informed decision. The discount rate plays an important role in determining whether action should be undertaken immediately, later or never (Stern 2006; Nordhaus 2007).

Two aspects of cost-benefit analysis that are important are uncertainty and futurity (Arrow 2007). Consequences of climate change in the absence of mitigation are highly uncertain, and estimated costs should account for that hence the discounting. The futurity is represented by the discount rate, or the rate at what future impacts (losses of future consumption) should be discounted to the present. The usual formula for discount rate is $\delta = \eta g + \rho$, where ρ is the social rate of time preference, g is the projected growth rate of average consumption and η is elasticity of social weight attributed to the consumption (Arrow 2007). There are two components to discounting the future. The first component is the term 'ηg' – this accounts for the fact that the future generations, assuming the economy grows in the long run as the evidence strongly indicate, will be wealthier than the current generation. In this case, discounting is appropriate on the basis of intergenerational equity. The second component of the discount rate 'ρ' represents the idea that a product today is the preferred and the same product tomorrow.

Stern (2006) was one of the first economists to address the issue of discounting in economic evaluations of climate change consequences. Stern used a 1.4% discount rate by setting the growth rate of the economy at 1.3%, the elasticity at 1 and the social rate of time preference at 0.1%. The controversy among economists involved the relatively low social rate of time preference and the elasticity. The author suggested that in evaluation of present costs of eliminating climate change consequences, one should not discount the wellbeing of unborn generations because of time preference. It is morally incorrect to set a positive social rate of time preference to unborn generations by the current living generations. This results in really small, near-zero (0.1%), social rate of time preference. But implications of such small social rate of time preference are worrisome for present generation, as mentioned by Nordhaus (2007). It was estimated that social rate of preference rate of 0.1 percent will result in considerable decrease of consumption today in order to insure the wellbeing of generations far into the future. Also a 1.4% discount rate does not reflect the present market rates and based on changes that are highly uncertain and appear in the far future.

Nordhaus (2007) is among the economists who criticized Stern's model. Using the Dynamic Integrated model of Climate and Economy (DICE), the author takes into account parameters that Stern missed, and comes up with the more realistic discount rate. According to Nordhaus (2007) the discount rate that is more plausible to use is 6%. This is composed of a growth rate of consumption at 2%, elasticity at more reasonable value of 2 and a social rate of time preference of 2%. The studies of Stern and Nordhaus are considered the benchmarks for the economic evaluation of climate change consequences. More often economists use the discount rate in between 1.4% and 6 %. According to Arrow (2007) the discount rate of 3 % is most consistent with current market traits and safe to use in calculations.

3.5. Putting it all together: The Grasslands Profit Potential Model

Grassland carbon profit potential demonstrates the best places to invest in grassland carbon on the basis of economic and biological conditions. The geography of profit potential therefore shows where the best investment locations are. The profit potential is calculated by combining the cost and quantity models with the market price for carbon credits by using the following model:

$$\textit{Profit Potential} = \$ = \left(P - OC_s\right) \times \left.\frac{tCO_2eq}{ha}\right|_G ; \tag{5}$$

where OC$_s$ is the social opportunity cost as indicated in (5). Price here is the market price for carbon credits that is determined by the overall demand and supply market conditions. Alternatively, the profit potential is:

$$\textit{Profit Potential} = \$ = \left(P - (OC_p + SB - SC)\right) \times \left.\frac{tCO_2eq}{ha}\right|_G ; \tag{6}$$

The social benefit of additional carbon sequestration would be calculated as follows:

$$SB = P \frac{\left.\frac{tC_{yearX}}{ha}\right|_{GG} 3.66 \frac{tCO_2eq}{C}}{\left.\frac{tCO_2eq}{ha}\right|_{G}} \tag{7}$$

Social costs can be estimated as the value society places on the overgrazed land, water contaminants, methane release and other problems associated with grazing adjusted for GC quantity of grasslands. The above profit potential provides information on resource allocation taking into account the private and social opportunity costs of the next best alternative (i.e., grazing). Profit potential from grazing will be always higher than not grazing as long as social benefits exceed social costs of grazing. If social benefits exceed social costs then society should have grazing on the land, otherwise society should keep the land pristine.

3.6. Results

3.6.1. Biology

Carbon content (C) for the 0-15 cm of soil profile at the upper elevation site was approximately two times higher than that of lower and middle elevations. For the 15-30 cm of soil profile, upper elevation had higher carbon content than lower elevation (see Chapter 2, Fig.2.4). Corresponding to the carbon content grassland carbon quantity has been computed for each elevation at two depths (Fig.3.4).

Grasslands carbon (GC) quantity, before any treatments were implemented, differed with the depth, both for lower and upper grasslands (Fig.3.4). Upper elevation grasslands had higher GC quantity than low and middle elevation grasslands at the 0-15 depth interval. GC quantity at the 15-30 depth interval was highest for upper elevation grasslands as well (Fig.3.4).

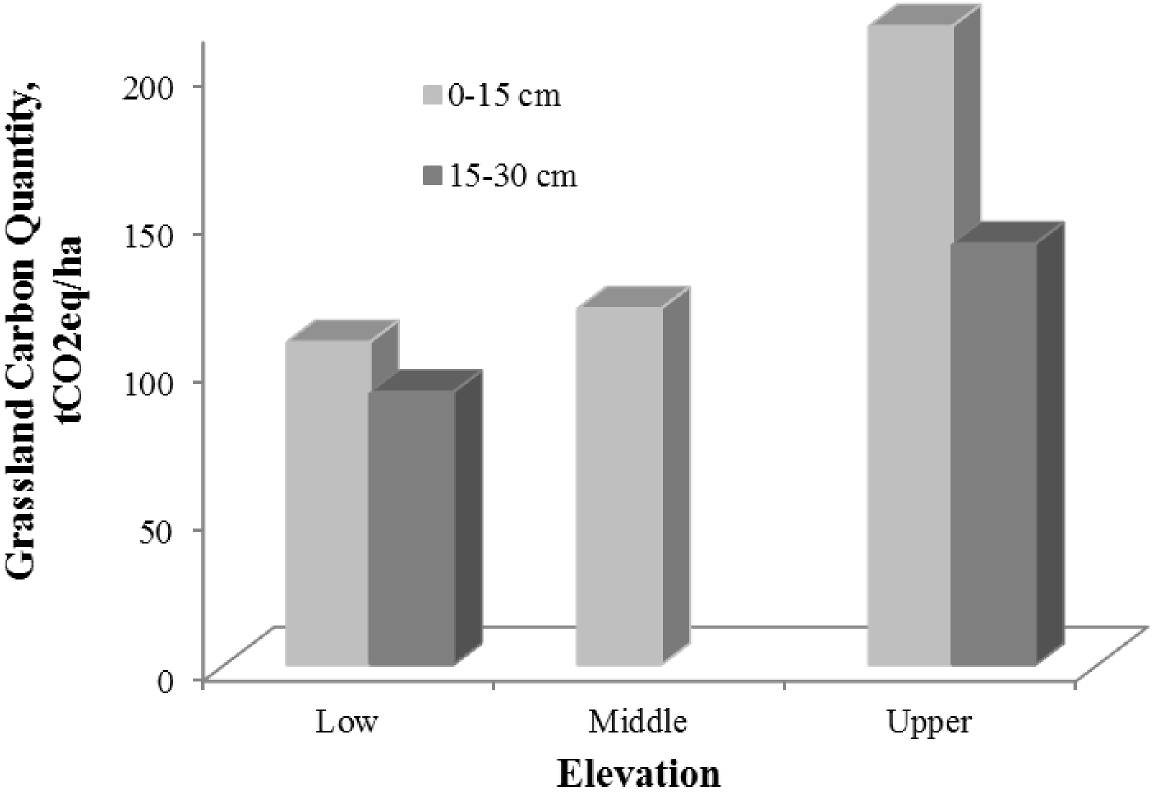


Figure.3.4. Initial Grassland Carbon quantity of different elevation grasslands at 0-15 cm and 15-30 cm depths.

Statistical analysis of soil carbon content at 0-15 cm depth showed significant influence of watering factor and interaction between factors elevation and clipping (See Chapter 2, Table 2.2).

Soil carbon content at the 0-15 cm depth was affected by the watering treatments (see Chapter 2, Table 2.2; Fig. 2.6). According to the 3-way ANOVA and Tukey post-hoc test, spring and fall watering treatments did not change carbon content levels significantly if compared to control plots (AMBIENT). Rain shade control plots (NO) showed no significant decrease in carbon content, if compared to the control (AMBIENT). But weekly fall waterings (WEEKFALL) showed significantly higher rates of change in carbon levels than rain shade control plots (NO).

A significant interaction between elevation and clipping was detected on soil carbon at 0-15 cm soil depth (see Chapter 2, Table 2.2, Fig.2.7). According to Tukey post-hoc test clipping treatments did not show any significant difference in means within low and middle elevations, as well as between them. Upper plots, that have been clipped, showed considerably higher rates of change (decrease) in carbon content than clipped plots at lower and middle elevation. Change of carbon levels at clipped and unclipped plots at the upper grasslands was not significantly different from each other.

Statistical analysis of carbon content at second respective depth (15-30 cm) did not show any significant effect of watering and clipping treatments. Only elevation was a significant factor according to 3-way ANOVA and Tukey post-hoc test (Table 3.1, Fig.3.2).

Based on experimental results of the field study the dynamic of GC quantity was calculated (Table 3.2). According to Figure 2.6 (see Chapter 2) the weekly waterings during fall (WEEKFALL) showed increase of 2.8 kg/ m^3, rain shade control plots (NO) showed decrease of 2 kg/ m^3 (which transfers to 0.72 kg per m^3 15 cm deep). Figure 2.7 (see Chapter 2) showed that clipping treatments at upper elevation resulted in decrease of carbon content at 3.3 kg/ m^3 (0.49 kg per m^3 15 cm deep), when low and middle elevation did not show any significant effects. Dynamic of carbon content due to precipitation treatments was calculated as a difference between NO and WEEKFALL. The difference for climate manipulations and rates of change for management treatments were multiplied by 3.66 conversion factor (to convert from metric ton of carbon into CO_2 equivalents) (see equation (2)) and 10000 to convert kg/ m^3 into t/ha.

Table 3.2. Dynamic of Grassland carbon quantity due to precipitation and management treatments

Treatments	**GC quantity dynamic, ——**
Precipitation	26.35
Clipping (grazing)	-17.93

3.6.2. Economy

Opportunity costs of land

The initial assumption about opportunity costs of generating grassland carbon at Lac du Bois was that we have to account for future foregone rents from the grass-fed cattle, because grazing is a main management practice for this area. Lac du Bois grazing schedule and amounts of AUM's is administered by the Range Use Plan. Presently, amount of AUMs that annually graze the grassland is 2797 (Lac du Bois Range Use Plan, 2010). The rent ranchers pay for grazing ($2.23 per AUM) and total area that are grazed (3300 ha), defines the total rent paid per ha, it is $1.90 per month. Considering that grazing period of Lac du Bois range is from May to November, it gives us total length of rental period per year – 7 months. The total rent paid by ranchers, therefore, is $13.30 per ha annually.

Grassland Carbon quantity that can be generated from the Lac Du Bois grasslands in conditions of changing climate (precipitation treatments) was 26.35 ——— (Table 3.2). Private opportunity costs of generating that carbon are calculated using equation (3). Assuming that discount rate is 3 %, the costs are $15.95 per tCO_2eq.

Field experiment showed that grazing influence is specific to elevation. The decrease in GC quantity at upper elevation was 17.93 ——— . It invoked additional social costs (for upper elevation grasslands) and resulted in change of opportunity costs (see equation (4)). Social costs of grazing are $1.45 per tCO_2eq. Therefore social opportunity costs are $ 14.5 per tCO_2eq (Table.3.3). As described in section 3.4.3 the discount rate of 3% reflects the current conditions of the market and preferable to use. But in case of market change opportunity costs will be changing as well. Sensitivity analysis of opportunity costs to the value of the discount rate is represented in table 3.3.

Table 3.3. Sensitivity analysis of grassland opportunity costs to the value of the discount rate

Scenarios	**Discount rate/ Costs in $ per ———**		
	1%	**3%**	**5%**
Private	31.81	15.95	10.01
Social	30.36	14.50	8.56

The sensitivity analysis indicates that the opportunity cost, private or social, per tCO_2eq, decreases with a higher discount rate. By using a higher discount rate the present value of future annual rangeland rent per hectare, $GFC/ha is valued lower. A higher discount rate results in a lower private opportunity cost and hence the social opportunity cost falls as social costs remain unchanged at $1.45 per tCO2eq.

Profit potential

The present market price of carbon credits is on average $20 per tCO_2eq (den Elzen et al. 2011). Opportunity costs of grassland carbon generation is $13.46 (for upper elevation) per tCO_2eq (Table 3.3). The average quantity of carbon at Lac du Bois presently is 143.83 ——— and it might be potentially increased (decreased) in conditions of changing climate and management practices by 26.35 and -17.93 ——— respectively.

Net Grassland Profit Potential (Net GPP) of Lac du Bois carbon stock and value per hectare are presented in Table 3.4. Here the GCQ column refers to grassland carbon quantity per hectare of the land, GPP column refers to grassland profit potential per one hectare, and Net GPP value refers to grassland profit potential per approximate size of each elevation (1100 ha). Upper elevation has higher value due to greater carbon quantity per hectare. Middle elevation grasslands have the lowest value, due to geological formation of the land and depth of soil profile. GPP here is calculated using the formula (5). Price of carbon is $20 per ton of CO_2eq.

Table 3.4. The Net Grassland Profit Potential of Lac du Bois carbon and profit per hectare

Area	**GCQ, ———**	**GPP, $ per hectare**	**Net GPP, ($ in millions)**
Lac du Bois average	245.87*	1351.18	4.46
Lower elevation	202.58	1114.19	1.22
Mid elevation	120.00	660.00	0.73
High elevation	415.04	2828.72	3.11

*Note: The average Lac Du Bois carbon quantity is computed as an average of the three elevations.

Profit potential rose by $145 per ha annually when climate change scenario was applied. In this case, the Net GPP of Lac du Bois increased by $ 0.48 million annually. In scenario where grazing were applied profit potential of one hectare went down at upper elevation by $99. It resulted in $ 0.325 million decrease (upper grasslands) of potential profits annually.

3.7. Discussion

The issue of climate change mitigation is directly connected to the reduction of CO_2 in the atmosphere. During the last couple of decades researchers have been looking for alternative ways of reducing emissions to the atmosphere and sequestration by the terrestrial ecosystems has been considered an option. However lack of scientific information and difficulty in economic assessment of ecosystems prevents sequestration projects from entering into political decisions.

Many studies have been conducted in order to inform policy decisions about the most effective ways of greenhouse gases (GHG) mitigation. Mostly those studies were devoted to abatement of GHG and only some of them considered carbon sequestration as a part of the mitigation strategy. The reason is carbon prices and biology of carbon sequestration (Lal and Bruce 1999; van't Veld et al. 2005). According to van't Veld et al. (2005) in scenarios when carbon prices are constant over time it is effective to use both sequestration and abatement projects, but when prices are changing (in this case rising) over time, delaying carbon sequestration projects becomes more reasonable. The main reason for such a delay is the biology of carbon sequestration. Lal and Bruce (1999) among others confirmed that sequestration is a time-limited process and with time sequestration rates might drop and sequestering lands might reach their full storage potential. This reason makes sequestration projects effective at constant prices and right now. If price of carbon would be consistently rising then the share of sequestration projects in GHG mitigation strategy will be dropping, as they become economically inefficient (van’t Veld et al. 2005).

Despite scepticism about carbon sequestration by terrestrial ecosystems, studies have shown a potential for additional carbon storage. Thompson et al. (2008) modeled potential rate of carbon sequestration by three ecosystem types over the next 100 years. According to their study agricultural lands stores 0.21 $GtCyr^{-1}$, reforestation stores 0.31 $GtCyr^{-1}$ and pasture lands stores 0.15 $GtCyr^{-}$1. Conant et al. (2001) estimated that grassland ecosystems under different management scenarios would be able to sequester 0.54 MgC per ha per year.

Similarly the present study supports findings of the above studies and indicates that grasslands are a source of ecosystem services that can’t be ignored and must be taken into account when making any policy or management decisions. The Proposed model estimated the value of Lac du Bois grasslands, in terms of already stored carbon, as $4.46 million, and potentially that value can be increased by $0.48 million annually, if precipitation events will occur according to modeled predictions. Results showed that management practices (grazing) have elevation specific influence. Grazing management of upper elevation grasslands should be sustainable, as high intensity grazing may result in loss of profit potential by $0.325 million annually.

The attempts to evaluate ecosystem services have been done by many researchers. One of the first to shed light on real value of natural capital was Costanza et al. (1997). He estimated that value of natural capital and ecosystem services it provides annually on a global scale is, on average, $33 trillion. The most recent study by Gascoigne et al. (2011) evaluated the economic assets of different land use scenarios in prairies. The estimated profit of preserving natural prairies was 1 billion dollars (69 million annually) over next 20 years. The figure is in the range with our finding of $9.4 million per year. The estimates for one of the world’s “hot spots” (Brazilian Pantanal lands) in terms of ecosystem services was $6000 per ha per year (Seidl and Moraes 2000**)**. British Columbia grasslands, according to our study, could generate around $1300 per ha per year in terms of carbon sequestration.

When carbon sequestration is considered for the lands associated with other uses, the opportunity costs plays important role in decision making. The cattle industry in BC is highly reliant on productivity of grasslands ecosystems. Currently the amount of grazing animals in BC is estimated as 525 000. Total revenue from BC's cattle industry is about $500 million annually (BC Cattleman Association 2010), which is roughly $952 per head per year. Our research showed unsustainable grazing management practices could inflict a total loss of 99 dollars per hectare.

Study of grasslands under different land use scenarios showed that generally practices that intend to increase forage production, leads to increased carbon sequestration (Conant et al. 2001). Fertilization and grazing of grasslands showed some positive influence on carbon content of grassland soils (Reeder 2002; Shuman et al. 1999). Mostly those results were related to increased productivity and biodiversity of plant communities. Despite social benefits of carbon sequestration such practices should be accepted with caution, as they imply social costs. Fertilization might lead to increased emissions of nitrous oxides to the atmosphere and pollution of ground waters (Shlesinger 1999). Heavy grazing might not have a positive effect on carbon sequestration, as accumulated carbon might be offset by the methane emissions from the cattle (Fleischner 1994). Other potential negative influence of heavy cattle grazing on grasslands might include pollution of ground waters, destruction of soil structure and decrease in biodiversity and productivity (Fleischer 1994). In the present study social costs of grazing was not accounted for, as very little data is available on the topic. Further research is necessary to determine the magnitude of these costs.

Presently, sequestration projects considered in the climate change mitigation policy are associated with forests. According to estimates by Costanza et al. (1997) the world's forests could contribute $684 billion per year in terms of carbon sequestration. The estimate for US forests is $6 billion per year (Pimentel et al. 1997). In the study by Deveny (2009), the revenue from forest carbon in Brazil (hot spot) annually was established at $6.9-8.8 billion, and stock value at $15.7 trillion. BC's grasslands have a value of $1 billion in terms of stored carbon and could provide additional $111 million annually. The $1 billion translates to $250 per person with the addition possible of $27.25. At the three percent interest rate, the $250 can be converted to an income perpetuity of the amount $8.25 per person per year which increases by $0.83 per person per year if proper management practices are implemented.

The net value of temperate grasslands of the world, if extrapolated from our results, is $1.22 trillion, and it could be increased by $134.1 billion annually. Our results seem to be in the range with the findings of Costanza et al. (1997) and Deveny (2009), whose model inspired our Grassland Profit Potential model. The estimates of Costanza et al. (1997) are much greater, what would be expected considering the extent of author’s estimates.

Summarising the discussion above, it is important to note that grassland carbon might be an option when considering CO_2 emissions abatement policy. The profit potential of world’s grassland carbon is in the range of trillions of dollars. But climate change and management of grassland ecosystems could easily tip this value either way. Although our study showed increase/decrease in value of grassland carbon due to climate change and grazing, it is good to remember that climate change projections for other areas of the world might be different, and not all pasture lands are managed properly. Additional research is necessary to provide a data for all possible climate change scenarios and management practices.

Chapter 4 – General conclusions, management implications and directions for future research

Conclusions

Temperate grasslands of the southern interior of British Columbia are small but unique ecosystems that are being threatened by a number of factors. Lac du Bois grasslands are an example of such threats. Invasive species, inappropriate grazing management practises and excessive recreational activities, such as off-road vehicle use, are a few problems. Climate change predictions for BC might increase the severity of impacts in some regions, while in others the additive effect of climate change will be positive (Hebda 1997). Monitoring of these changes and appropriate decision making about management would maintain or increase grassland production of different ecosystem services.

Carbon sequestration, as one of ecosystems services provided by grasslands, was assessed in this thesis. Elevation difference in carbon content found here was consistent with the results of previous studies (Lee 2011; Evans 2011). The most likely cause for elevation differences in carbon content is increase of annual precipitation and plant productivity (van Ryswyck 1949). Carbon content of grassland soils decreases with depth, but upper elevation soils consistently show higher levels of carbon than low and middle elevations. Manipulations of precipitation patterns showed that increase in water availability led to increase in carbon load of soils. Seasonality and frequency of rainfall events influenced the ability of grasslands to store carbon in the soil. Predictions for BC in terms of climate change suggest that amount of fall precipitation will increase and rainfall events will occur more often. Modelling showed that such scenario might positively influence carbon content of soils. Shift of precipitation to the spring more likely will cause release of carbon from the soil due to increase in respiration rates. That assumption was supported by the results of Net Carbon Exchange measurements. NCE was higher during spring watering period. Clipping treatments did not show significant effect on NCE rates, but decrease in carbon content of upper elevation grasslands was detected after clipping treatments were applied.

Timing of grazing influenced accumulation of grassland carbon. A pasture consistently grazed during fall showed higher carbon content than the pasture grazed during spring. Respiration rates were higher for spring grazed pastures, which might explain lower carbon content.

Results of field experiments regarding carbon content and carbon flow were used to estimate the monetary value of Lac du Bois carbon storage. The Carbon Profit Potential model has been developed to make this estimate possible. According to our findings, Lac du Bois grasslands provide $4.46 million in terms of already sequestered carbon, and this value could be increased by $0.48 million annually if precipitation events will behave as predicted. The extrapolation to the grasslands of British Columbia showed a significant value of $1 billion and flow of $111 billion annually. That value is representative of $250 per person with the addition possible of $27.25. At the three percent interest rate, the $250 can be converted to an income perpetuity of the amount $8.25 per person per year which increases by $0.83 per person per year if proper management practices are followed.

Management implications

Lac Du Bois grasslands is a combination of grassland communities that are representative of other British Columbia grasslands (Basset 2009). Traditionally, those grasslands are used for cattle grazing. Data about influence of grazing on grassland ecosystem services are required in order to make informed and sustainable management decisions.

Carbon sequestration is an important ecosystem service provided by grasslands. This service has a potential to influence carbon balance of the atmosphere and might be the way of mitigating climate change. Results of my study showed that change in precipitation patterns influenced carbon content of soils. Net Carbon Exchange measurements showed that spring precipitation increases respiration rates of ecosystems. These findings will be useful when any adjustments to current grassland management plans are made in order to address potential influence of climate change.

Clipping grasses to a stubble height of 5 cm, which is considered heavy grazing, influenced carbon storage negatively at upper elevation grasslands. These results imply that high stocking rate grazing has a negative influence on carbon storage at upper elevations. Fall grazing at middle elevation is more favourable then spring grazing, and results in increase of carbon storage.

Outcomes of the economic assessment of grassland ecosystem services showed that grasslands carry a significant monetary value in terms of already stored carbon. Ability of grasslands to sequester additional carbon as a result of climate manipulations confirmed the possibility of grasslands acting as carbon sink. It was found that on a yearly basis Lac du Bois grasslands could sequester $9.4 million worth of carbon. The values reported in this thesis might be the grassland base line for entering the carbon market.

Future research directions

My research provided the base line for future research of carbon storage in grassland communities. I tested the dependence of grassland carbon on frequency and seasonality of precipitation events. Although the design of my experiment reflected the predictions of climate change models for BC, it would be informative to combine seasonality, frequency and amount of precipitation event and see if any variation in grassland carbon occurs. The duration of the experiment might introduce new prospective. Although the findings of my two year study are useful, a long term experiments will provide more information about year to year chan3ges. *Further* research is required to determine the full scope of grazing influence on carbon storage of soils. Here the modelling of timing, intensity and seasonality of grazing might provide useful insights on the carbon sequestration during the growing season.

My estimations of total grassland carbon quantity are lower than real values, as we sampled only first 30 centimetres of soil profile. Sampling of soil profiles up to 1 meter would provide more realistic carbon content values. Although the extrapolation to all British Columbia grasslands was made here, the differences in conditions and ecosystem compositions are different throughout BC grasslands. Expansion of research to the provincial scale will reveal whether all temperate grasslands react to the changes similarly or different ecosystem types tend to react differently. The full scope of information about grassland in BC will help to reveal weak and resistant ecosystems and will provide information for management decisions on provincial level.

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APPENDIX A

Table A.1. Results of ANOVA for soil moisture data. Bold indicates significant results at p<0.05.

Treatment	**Df**	**Mean Sq**	**F-ratio**	**P**
Water	**5**	**0.014**	**4.628**	**0.0005**
Clipping	1	0.003	1.175	0.2799
Elevation	2	0.013	1.609	0.2031
Water × Clipping	**5**	**0.040**	**2.515**	**0.0316**
Water × Elevation	10	0.054	1.678	0.0894
Clipping × Elevation	2	0.000	0.075	0.9281
Water × Clipping × Elevation	10	0.006	1.784	0.0668

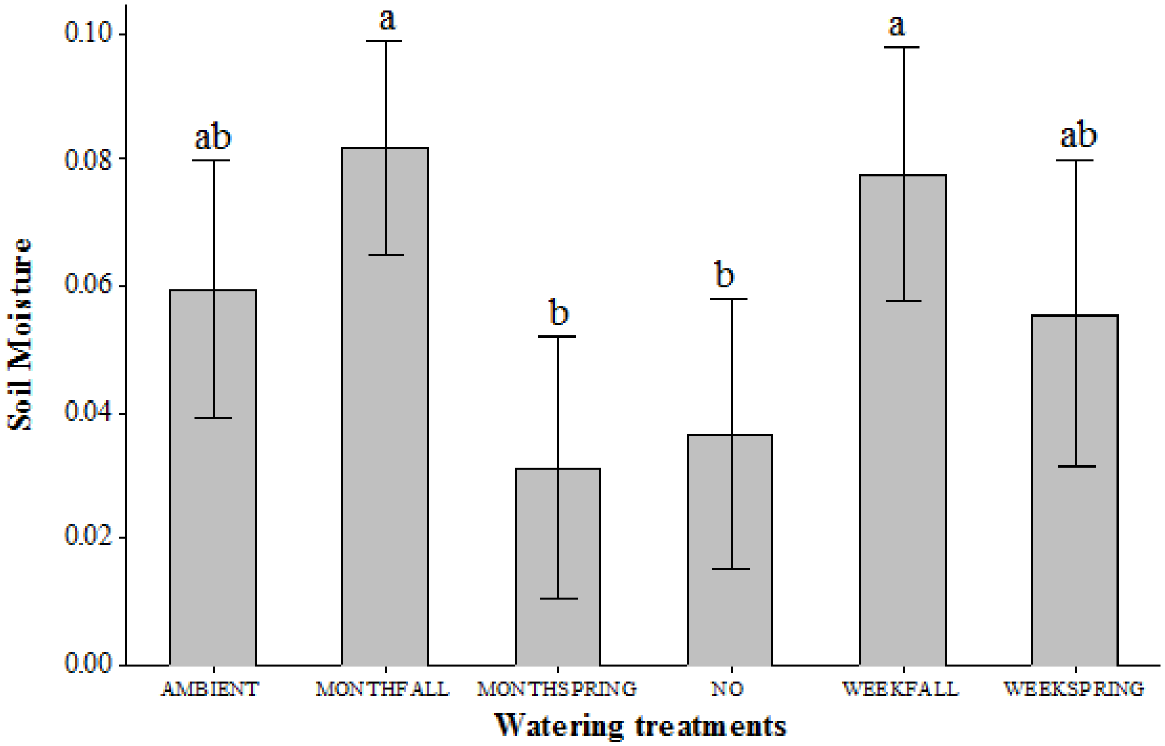

Figure A.1. Influence of watering treatments on soil moisture. Same letters indicate the insignificant difference according to Tukey post-hoc test.

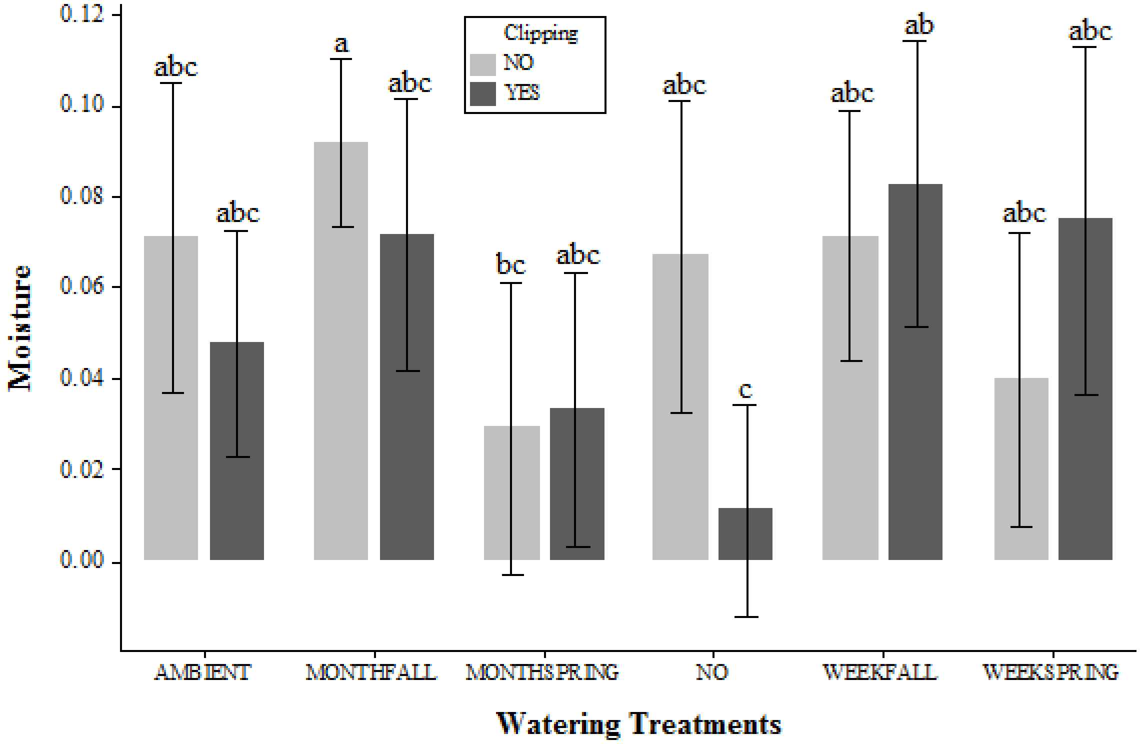

Figure A.2. Interacting effects of watering and clipping treatments on soil moisture. The same letters indicate not significant difference according to Tukey post-hoc test.

APPENDIX B

Table B.1. Results of ANOVA for soil temperature minimum. Bold indicates significant results at $p<0.05$

Treatment	**Df**	**Mean Sq**	**F-ratio**	**P**
Water	**5**	**100.3**	**3.353**	**0.007**
Clipping	1	12.8	0.427	0.514
Elevation	**2**	**193.4**	**6.467**	**0.002**
Water × Clipping	**4**	**325.8**	**10.892**	**9.48e-08**
Water × Elevation	**8**	**178.8**	**5.980**	**1.26e-06**
Clipping × Elevation	**2**	**217.5**	**7.272**	**0.001**
Water × Clipping × Elevation	6	179.2	5.991	1.28e-05

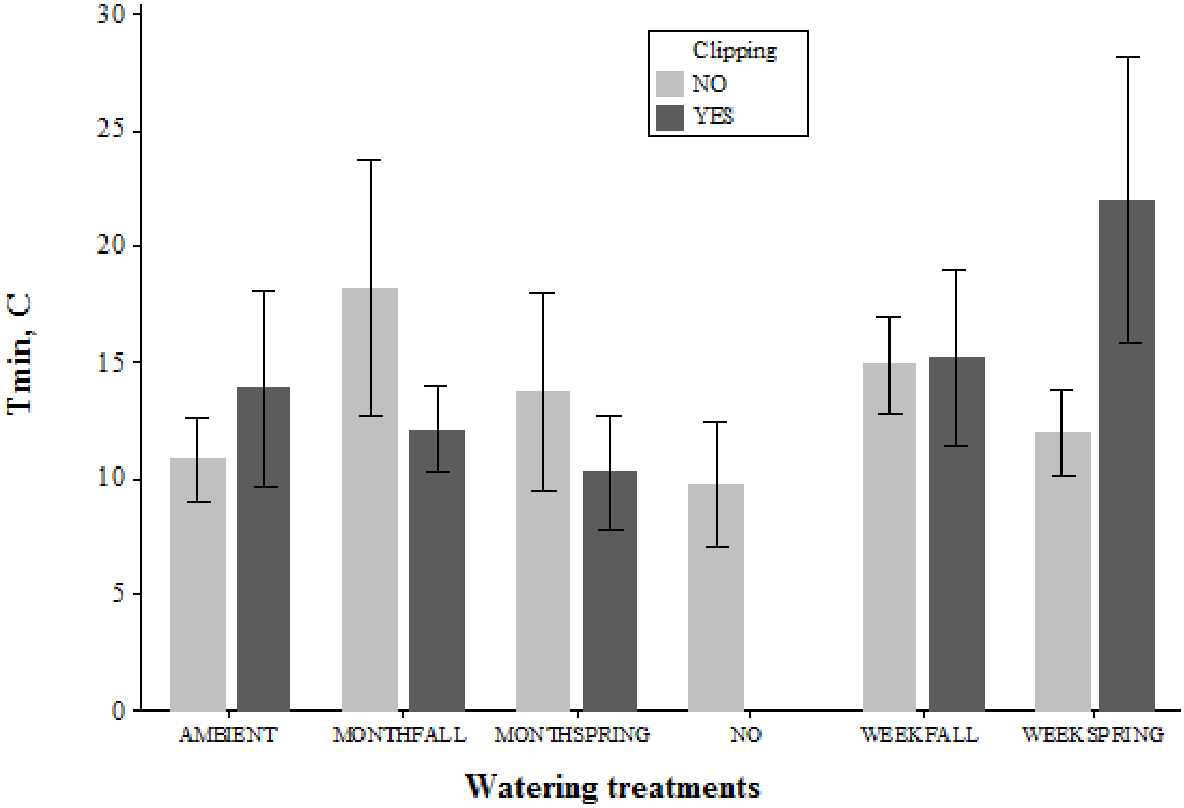

Figure B.1. Interacting effects of watering and clipping treatments on soil temperature minimum.

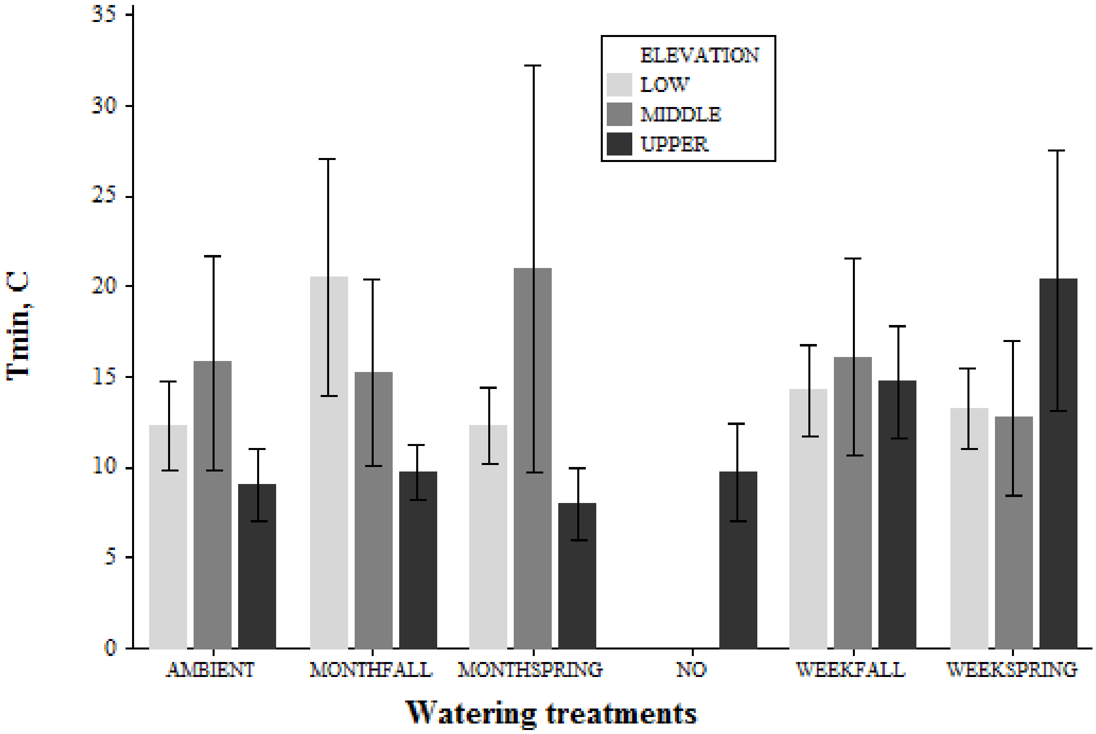

Figure B.2. Interacting effects of watering and elevation on soil temperature minimum.

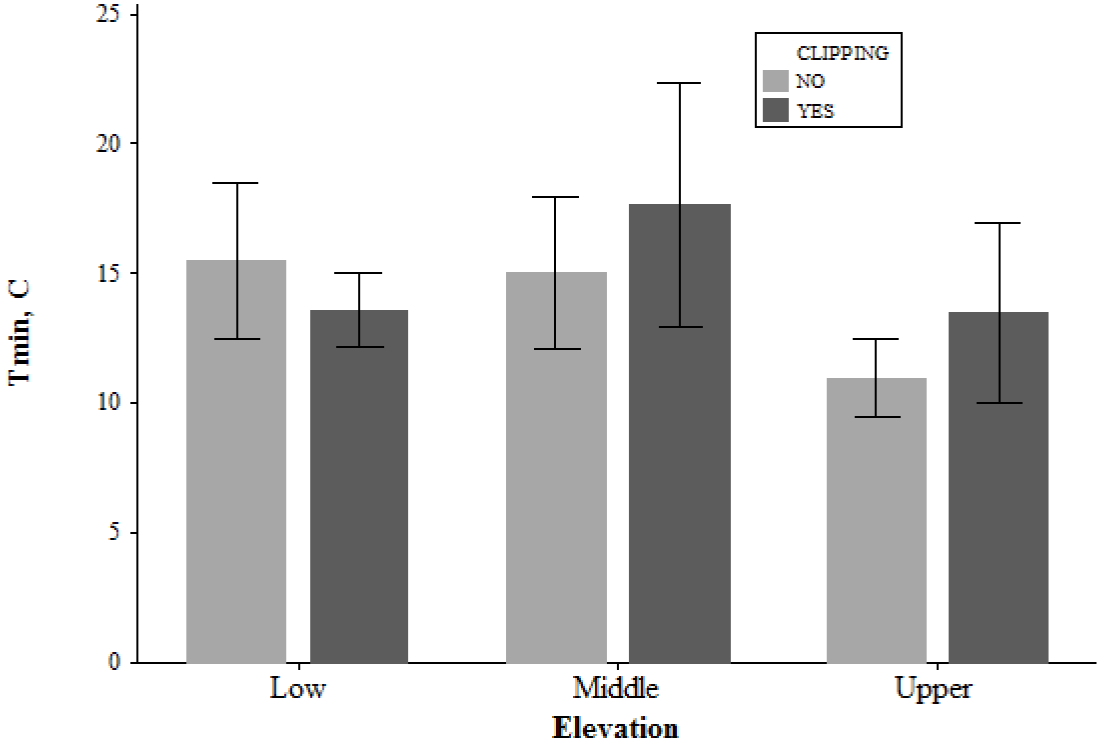

Figure B.3. Interacting effects of elevation and clipping on soil temperature minimum.

APPENDIX C

Table C.1. Results of ANOVA for soil temperature maximum. Bold indicates significance at $p < 0.05$.

Treatment	Df	Mean Sq	F-ratio	P
Water	5	109.7	1.186	0.318
Clipping	1	13.5	0.146	0.703
Elevation	**2**	**1608.3**	**17.392**	**1.7e-07**
Water × Clipping	**4**	**280.0**	**3.028**	**0.019**
Water × Elevation	8	45.0	0.486	0.846
Clipping × Elevation	2	95.3	1.031	0.354
Water × Clipping × Elevation	6	145.4	1.572	0.159

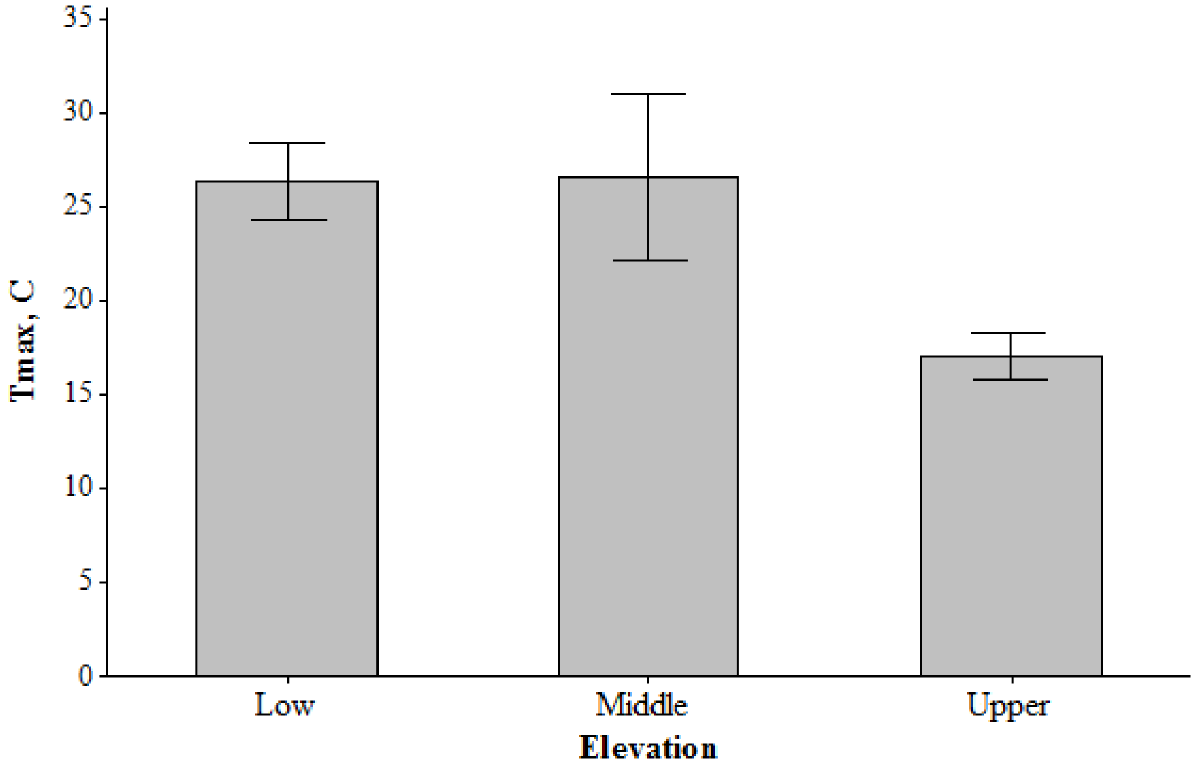

Figure C.1. Difference in soil temperature maximum with elevation.

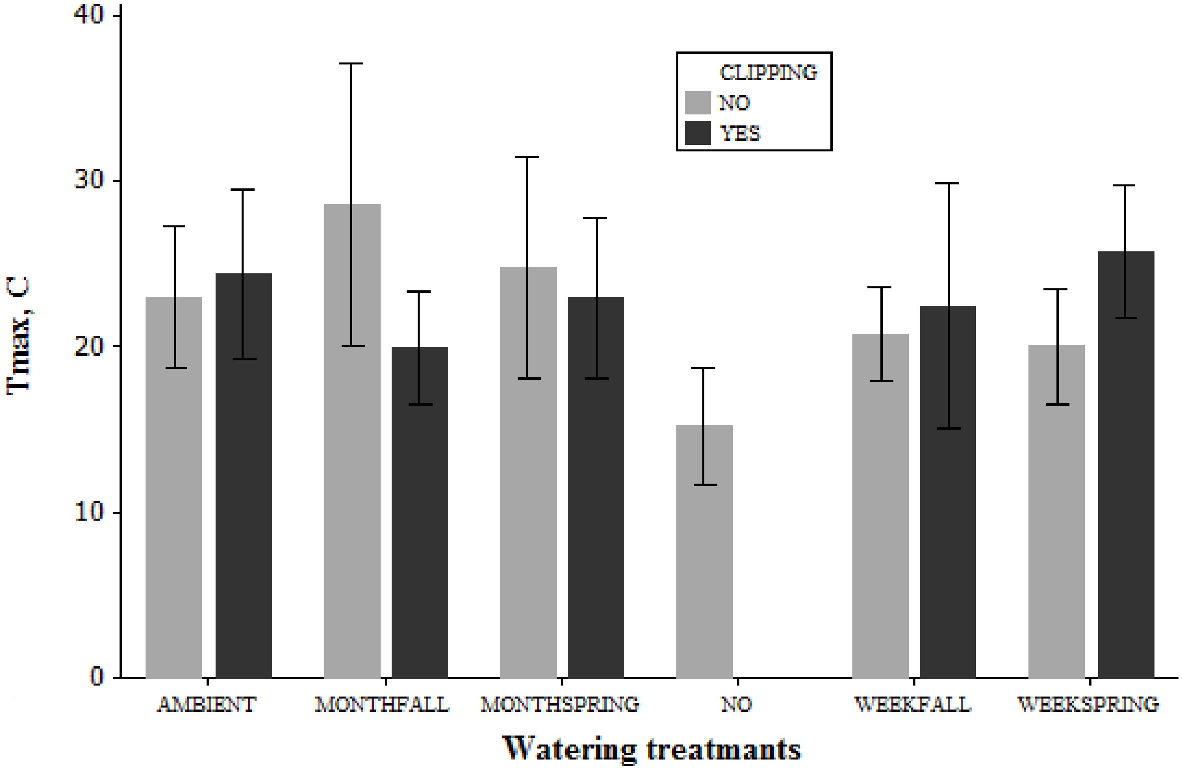

Figure C.2. Interacting effects of watering and clipping treatments on soil temperature maximum.