Climate change and the provision of ecosystem services in Alberta:

an initial assessment of impacts and adaptation strategies on Alberta's rangelands

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Preface:

The Alberta Biodiversity Monitoring Institute (ABMI) is an arm's-length, not-for-profit scientific organization. The primary goal of the ABMI is to provide relevant scientific information on the state of Alberta's biodiversity to support natural resource and land-use decision making in the province.

In the course of monitoring terrestrial and wetland ecosystems across the province, the ABMI has assembled a massive biodiversity database, developed reliable measurement protocols, and found innovative ways to summarize complex ecological information.

The ABMI undertakes focused projects to apply this capacity to specific management challenges, and demonstrate the value of the ABMI's long-term monitoring data to addressing these challenges. In some cases, these applied research projects also evaluate potential solutions to pressing management challenges. In doing so, the ABMI has extended its relevance beyond its original vision.

The ABMI continues to be guided by a core set of principles – we are independent, objective, credible, accessible, transparent and relevant.

This report was produced in support of the ABMI's Biodiversity Management and Climate Change Adaptation and Ecosystem Services Assessment projects.

The views, statements, and conclusions expressed in this report are those of the author(s) and should not be construed as conclusions or opinions of the ABMI. The ABMI is a value-neutral organization committed to the application of high quality science to natural resource management in Alberta.

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Abstract

Ecosystem services are the benefits people receive from nature that contribute to our health and well-being. Climate change is anticipated to have numerous and wide-ranging effects on the provision of many ecosystem services, which may have serious consequences for the people, communities, and industries that rely on those services. Understanding these impacts, as well as the costs and benefits of potential adaptation strategies is therefore critical for long-term social, environmental, and economic planning. We examined two important ecosystem services in Alberta's native grasslands: soil carbon storage for climate change mitigation and aboveground biomass production (i.e. forage) for livestock grazing. We developed a comprehensive carbon dynamics model for this region using the CENTURY carbon model, and used it to assess the impacts of recent and future climate change on the provision of these two ecosystem services, and the potential for grazing management as a long-term climate change adaptation strategy to maintain these processes over the long term. Based on a preliminary analysis, modelled aboveground biomass and soil carbon storage increased or remained stable in response to both recent historical climate change and projected future climate change up to mid-century (2050s), suggesting that the these processes may be enhanced by climate change over the medium-term. However, declines in both ecosystem processes were predicted toward the end of the century (2080s). These modelled responses were sensitive to grazing intensity, with low-intensity grazing typically resulting in increases in both processes over recent years and in projected future conditions. This suggests that grazing management has the potential to be a useful adaptation measure to respond to the impacts of climate change on aboveground biomass production and carbon storage in rangelands soils. We are continuing to work on model calibration and validation to improve our estimates of carbon storage and aboveground biomass production. Further, we are working towards an integrated model to estimate how multiple ecosystem services respond to a single management activity, which is critical to support a more complete cost-benefit analysis of potential climate change adaptation strategies.

Introduction

Ecosystem services (ES) are the benefits people receive from nature, including carbon storage for climate change mitigation, forage production for wildlife and livestock grazing, clean water for human consumption, and many others (Millennium Ecosystem Assessment 2005). These benefits are best viewed as end-products directly used and enjoyed by humans that are generated from the interaction of many biophysical processes (Kareiva et al. 2011; Haines-Young & Potschin 2010; Boyd & Banzhaf 2007). For example, the benefit of recreational fishing is the end-product of a long series of linked processes such as nutrient cycling, photosynthesis, water cycling, water temperature, and fish productivity (Keeler et al. 2012).Climate change will alter the processes of these biophysical systems, with numerous and wide-ranging potential effects on the provision of ES and the well-being of the people who rely on those services (Shaw et al. 2011; reviewed in Nelson et al. 2013; Staudinger et al. 2012; Schroter et al. 2005).

Land management choices are a primary means of adapting to changes in biophysical processes as a result of climate change and, in some cases, such choices can also support climate change mitigation (e.g., through enhanced carbon storage in soils). Climate change adaptation through land management could include changes in timber harvest plans in response to changing forest productivity (Gauthier et al. 2014), conversion of uncultivated land to cropland to capitalize on expanding agricultural climate zones (Thorpe 2012; Howden et al. 2007), or changes in grazing regime in response to altered rangeland productivity (Thorpe 2012; Howden et al. 2007; Christensen 2004).

As the end-products of various inter-related biophysical processes, ecosystem services do not vary independently of one another (Kirchner et al. 2015), so the responses of a suite of linked ES to a stressor such as climate change may vary in both strength and direction (Staudinger et al. 2012; Montoya & Raffaelli 2010). Consequently, climate change adaptation strategies intended to support the provision of one ecosystem service could result in losses of another service. A comprehensive understanding of the impacts of climate change on ES provision and the effectiveness of potential adaptation strategies will require an integrated, systems-based approach that evaluates multiple ES simultaneously under current and future land management and climate regimes (Byrd et al. 2015).

Alberta communities rely on the provision of ecosystem services from natural systems. Understanding 1) the potential costs and benefits of climate change for a suite of ecosystem services, and 2) the potential costs and benefits of specific, actionable adaptation strategies will be valuable to communities working to identify climate change risks and evaluate adaptation strategies to address those risks.

Ecosystem Services Assessment Project

The ABMI's Ecosystem Services Assessment (ESA) project[1] is developing an integrated set of ecosystem service models to assess the provision and value of multiple services in Alberta. Current ES models include: water purification, rangeland carbon storage, rangeland forage production, timber harvest,

[1] www.ecosystemservices.abmi.ca

forest carbon storage, and canola pollination. Because climatic variables are fundamental data inputs into several of the ES models, in particular the water supply and purification and rangeland carbon storage and forage production models, we are able to assess the potential changes in ES provision under future climate scenarios by incorporating future climate projections.

In addition to present and future climate scenarios, we will also be able to examine how land management choices may be used to mitigate the impacts of climate change. For example, recent studies have identified grazing as an important regulator of the responses of the grassland carbon cycle to climatic changes (Vaisanen et al. 2014; Polley et al. 2008). Alterations to grazing management practices could act as one adaptation strategy to maintain or enhance the carbon storage function of rangeland soils and maintain or enhance aboveground biomass production to ensure the long-term sustainability of cattle production. A diversity of adaptation options will be required in different rangeland regions to enhance social and ecological resilience, however (Ash et al. 2012).

Development of the ecosystem services models, including refinements to incorporate climate change, is ongoing. Here we present initial estimates from the rangeland carbon model, focusing on aboveground biomass production and soil organic carbon to represent carbon storage. We examine: 1) the effects of recent climatic change in Alberta on estimated rangeland top soil carbon storage (0-20 cm depth) and aboveground biomass production, and 2) the potential effects of future climate change in Alberta on rangeland aboveground biomass. While biomass production captures all above-ground growth, only a proportion of this biomass will be grazed by cattle representing the end-product that provides a benefit to people. For both analyses we include three simulated grazing intensity regimes to understand the potential for grazing management to be used as a climate change adaptation strategy for the maintenance of these processes on the Alberta's rangeland.

The model estimates and analyses presented in this report are preliminary and are subject to change. Future work, including assessment of uncertainties in the model estimates, will refine these outcomes to ensure they are sufficiently relevant and accurate to evaluate potential trade-offs in the supply and value of ecosystem services in present and future climate conditions to support decision-making.

Modelling carbon storage and aboveground biomass production in Alberta's native grasslands

We established a comprehensive carbon dynamics model for Alberta's native grasslands using the well-evaluated and extensively implemented ecosystem carbon model CENTURY (Feng & Zhao 2011; Smith et al. 2009). The CENTURY model requires data on monthly climate (e.g., rainfall and minimum and maximum temperature), soil properties (e.g., soil texture, depth, bulk density, drainage class and pH) and fire and management regimes (i.e., grazing history) for each location modelled (NREL 2009; Parton et al. 1988). CENTURY model outputs can be made spatially explicit by conducting model runs for a range of point locations that represent soil and climatic conditions across a region.

Model set up

The Agricultural Region of Alberta Soil Inventory Database AGRASID 3.0 describes the spatial distribution of almost 2100 soil types within the agricultural region of Alberta using 28,368 polygons with unique specifications for soil properties at a scale of 1:100 000 (ASIC 2001). Alberta is subdivided into 24 soil correlation areas (SCAs) that generally agree with natural ecoregion boundaries and correlate strongly with soil zone lines, with further subdivisions reflecting recognized agroclimatic zones (Brierley et al. 2008); each AGRASID polygon is associated with a SCA.

We used the AGRASID to build a soil database for native grasslands of Alberta, with the AGRASID polygons serving as spatial unit for our grassland carbon model. Polygons that had no information on a dominant native (versus agricultural) soil type, were associated with organic soils (e.g., wetlands), or were located in subalpine and alpine areas, were excluded. We subsequently extracted soil polygons associated with native grassland areas, as determined from the Alberta Biodiversity Monitoring Institute's (ABMI) Wall to Wall Landcover (v 1.0; ABMI 2012a) and Human Footprint maps (v 1.1; ABMI 2012b). This resulted in 25,093 soil polygons comprising 1491 soil types associated with 17 grassland SCAs. The number of SCAs was further reduced to nine SCAs by combining those that were comparable in terms of soil zone, ecoregion and agroclimatic zone (Table 1, Fig. 1). These nine SCAs represent distinct grassland sub-regions with unique soil and climate conditions. To accommodate regional differences in climate and vegetation across the province, which could influence soil carbon and biomass production dynamics, we developed regional carbon models for these nine soil correlation areas (SCAs) in Alberta's native grassland (Table 1, Fig. 1). While CENTURY provides several output variables reflecting soil carbon dynamics and vegetation growth, here we discuss the results for soil organic carbon (SOC; carbon contained in the organic matter in the top 20 cm of the soil profile) and aboveground biomass (AG biomass).

Historic climate data (1901-2011) for each AGRASID polygon were extracted from ClimateWNA (Wang et al. 2012), which provides gridded monthly, seasonal and annual climate data at a resolution of 2.5 acrmin x 2.5 arcmin (approx. 4 x 4 km) based on interpolated historical weather station records. Actual monthly weather data were used for years 1901-2011, while averages for this period were used for years prior to 1901.

Soil and plant nitrogen content influences the overall turnover rates of organic carbon in grassland ecosystems (Parton et al. 1988, Liu et al. 2005, de Graaff et al. 2006). To consider this, we used available literature to define rates for atmospheric nitrogen deposition (Alberta Environment 2006) and biological nitrogen fixation (Cleveland et al. 1995), and the carbon-to-nitrogen ratios (C/N) in litter and mineral soil (Murphy et al. 2002; Smith et al. 1997). Because information for these parameters is not available for each SCA, these values were kept consistent across all SCAs for this initial assessment (Lugato et al. 2014). The remaining parameters of the CENTURY model were based on extensive experiments and validation from Great Plains grasslands (Parton et al. 1988), of which Alberta rangeland is a northern extension. Vegetation parameters suggested for temperate, C3 vegetation were modified for Alberta's rangeland, based on consultations with other CENTURY users (CENTURY Core Group at Colorado State University; C.G. Tornquist, pers. comm.). All other parameters were left to default values or, in the case of initial soil organic matter, established through equilibrium.

Table 1. Characteristics of nine SCAs defined for native grasslands of Alberta. SCA names are defined based on the characteristics explained for each SCA code in Alberta soil names file (Generation 3) user's handbook (Brierley et al. 2006). Agroclimatic zones are based on categories defined by Alberta Soils Advisory Committee (ASAC 1987).

Combined SCA name	Original SCA code(s)	Agroclimatic zone	AGRASID	
			Soil types	Soil polygons
Brown Soil of Dry Mixedgrass	1	3A	75	4688
Dark Brown Soil of Mixedgrass	2,3	2AH, 2H	77	2012
Dark Brown Soil of Northern Fescue	4	2AH	39	2736
Thin Black soil of Foothills Fescue	5,6	2AH, 3H	49	1521
Thin Black soil of Central Parkland	7,9	2H, 3H	39	1753
Thin Black Soil of Foothills Parkland	8,13	4H	66	1929
Thin Black-Dark Gray Soil of Parkland, Mixedwood	10	2H, 3H	84	3268
Dark Gray-Black Soil of Dry Mixedwood	12,18	2H, 3H	106	2151
Dark Gray-Gray Soil of Mixedwood	17,20,21, 22	4H (5H)	123	1495

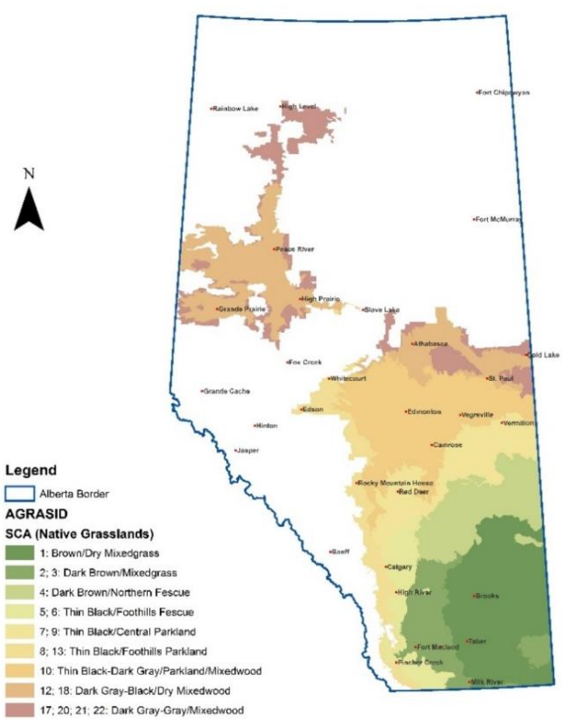

Figure 1. Distribution of soil correlation areas used to define regional models of rangeland carbon dynamics for Alberta.

Model runs

We ran the model for two time periods. First, we ran a 4900 year equilibrium block, using 1901-1990 climate averages (Wang et al. 2014; Parton et al. 1988). CENTURY also requires specification of management activities. For the equilibrium period, we specified a fire event every six years and a bison grazing event in two months (shifting by two months) out of every year (Wang et al. 2014). We then ran a 110 year period (1901-2011) using monthly weather records. For this latter period, we removed fire events, as fire has been largely suppressed since European settlement. We also specified cattle grazing during the months of June, July and August (Wang et al. 2014), under three hypothetical grazing regimes defined according to the proportion of aboveground biomass that is removed each year by grazing: 30%, 50% or 70%, corresponding to low-, moderate-, and high- intensity grazing, respectively. The same grazing regimes were used to assess potential changes in grassland carbon under future climate projections. These hypothetical grazing regimes represent one example of how changes in grazing management can be modelled in CENUTRY; other applicable and relevant grazing management scenarios, including those that vary grazing season duration or region of application of different grazing intensity regimes, will be considered for further analysis.

Future climate conditions

Future climate conditions (monthly rainfall and minimum and maximum temperatures) were represented by 30-year monthly averages for the 2020s (2011-2040), 2050s (2041-2070), and 2080s (2071-2100) from an ensemble of 23 CMIP3 global climate models (Meehl et al. 2007) available through ClimateWNA (Wang et al. 2012). We used future climate projections based on the A2 emissions scenario (IPCC 2001), which most accurately reflects the current trend in global carbon emissions (Friedlingstein et al. 2014). These future climate projections were implemented in CENTURY by simulating a single year with average climate conditions projected for each of the three future time periods (i.e., three following years for 2020s, 2050s, and 2080s).

Our use of 30-year average projected climate conditions as a single year might better predict the potential impacts of climate change on plant growth, which responds quickly to inter-annual climatic variability, though plant growth is also strongly controlled by nutrient availability (de Graaff et al. 2006). However, this simulation approach might not adequately predict changes in soil carbon storage, which responds gradually to changes in climatic conditions over time. Climate projections with finer temporal resolution (e.g., monthly data for each year, rather than averages) are required to adequately represent gradual changes in soil carbon. Therefore, we present only preliminary results for the potential changes in aboveground biomass in response to future climatic changes. To assess future changes in organic carbon storage in Alberta's rangelands, we plan to use finer temporal resolution climate projections from regional and global climate models.

The results presented here are based on our initial model that does not represent variation among SCAs in model parameters that could influence plant growth and carbon cycling (e.g., optimum temperature for decomposition, optimum temperature for plant growth). Calibration of the regional models for each

SCA to achieve more realistic variable and parameter sets for each of the nine regions is ongoing. To calibrate the SOC estimates from the regional models, we will use soil carbon data from mineral soil samples collected by ABMI at approximately 400 sites spaced throughout Alberta's grasslands (ABMI 2014a, b). We will also calibrate the AG biomass estimates from the regional models using long-term biomass and forage production data generously shared by the Alberta Environment and Sustainable Resource Grazing and Range Management Group (unpubl.). Finally, we will validate model estimations using measured above- and below-ground plant biomass and SOC data collected by the Rangeland Research Institute at University of Alberta[2] (Bork and Carlyle, unpubl.). Separate calibration and validation of a carbon model for each SCA will more accurately represent carbon dynamics throughout Alberta's native grasslands. It also will enable an assessment of the uncertainties in the model estimates so that we can evaluate the level of precision achieved in our simulations of grassland carbon across different regions.

Model initialization is a crucial part of carbon modelling (e.g., Hashimoto et al. 2011), as incorrect initialization of carbon pools potentially leads to incorrect assessments of gradual changes in SOC over time. However in a relatively undisturbed land-use system, such as native grasslands, projections of organic carbon under climate change are relatively insensitive to the model initialization (Senapati et al. 2013). Further, in this initial assessment, we focus on relative changes in grassland carbon storage (AG biomass and SOC) among time periods. Therefore, the results from the uncalibrated model remain useful to predict future changes in grassland carbon storage under different land management and climate change scenarios.

Data analysis

We examined the effects of recent and future climate changes and the potential effects of grazing intensity on grassland carbon storage by evaluating the changes among time periods under three different grazing intensity regimes. For recent climate change, we modeled the change in AG biomass and SOC between two 20-year periods: the 1970s (1961-1980) and the 2000s (1991-2010) under each grazing regime. For future climate change impacts, we modeled the change in AG biomass between the historic period of 1961-1990 (1970s) and each future period (2020s, 2050s, and 2080s) under each grazing regime.

[2] http://www.rri.ualberta.ca/en/Research/CarbonSequestration.aspx#CarbonStocks

Effects of recent climate change and grazing regime on SOC and AG biomass

While there was little observed change in annual precipitation between the 1970s and the 2000s, there was an overall increase in minimum and maximum temperature (Fig. 2) that was most apparent in the cooler SCAs in central and northern Alberta (Dark Brown Soil-Northern Fescue; Dark Gray/Black Soil-Dry Mixedwood; Dark Gray/Gray Soil-Mixedwood; Thin Black/Dark Gray Soil-Parkland). This heterogeneous warming further justifies the use of regional models for examining the potential impacts of climate change on rangeland biomass production and carbon storage.

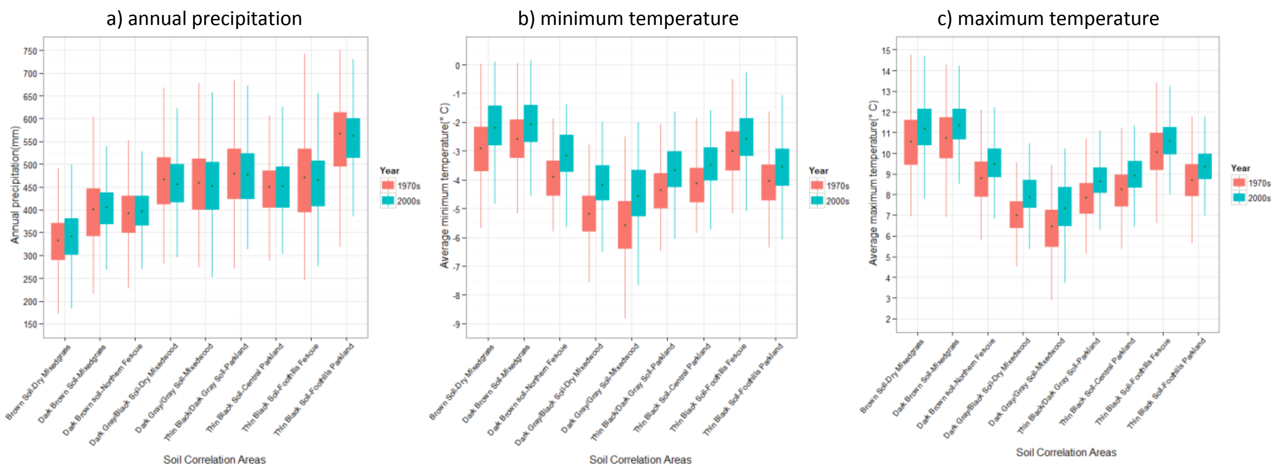

Figure 2. Annual climate conditions in each soil correlation area for three climate variables used as input to the CENTURY model for the 1970s (1961-1980) and 2000s (1991-2010). For each time period and SCA, mean values (point), middle quartiles (25%-75%; box) and maximum and minimum values (lines) are presented, representing the variation among AGRASID polygons within each SCA.

The modeled response of aboveground biomass to the recent observed changes (i.e., warming) in climate between the 1970s and 2000s varied among regions and with grazing regime, from an average of an approx. 7% increase in the Brown Soil-Dry Mixedgrass under low-intensity grazing, to an average decrease of approx. 5% in the Thin Black/Dark Gray Soil –Parkland under moderate-intensity grazing. Variation within SCAs was highest under the low and moderate grazing regimes (Fig. 3a).Overall, the model predicted gains in AG biomass between time periods under low-intensity grazing, whereas relatively little change or reductions in estimated AG biomass between periods were predicted under moderate- and high-intensity grazing. However, the response of modelled changes in AG biomass to alternative grazing regimes varied among SCA regions.

The modeled changes in soil organic carbon between the 1970s and 2000s also varied among SCAs and grazing regimes, from an average increase of approx. 4% in the Brown Soil-Dry Mixedgrass region under low grazing to an average decrease of approx. 7% in the Thin Black Soil – Foothills Parkland region under high grazing (Fig. 3b). In contrast to aboveground biomass, the pattern of change in modeled SOC between time periods in response to grazing regime was more consistent among SCA regions, with high-intensity grazing typically resulting in the greatest decrease in SOC. Compared to the variation in response to grazing regime and among regions, variation within regions in the change in SOC was relatively small. In SCAs in the Mixedwood and Parkland regions where observed warming was greatest, the decrease in SOC was more similar between moderate- and high-intensity grazing regimes than in the Mixedgrass and Fescue regions of the province, where moderate grazing typically resulted in a smaller average decrease in SOC. This outcome highlights the joint effects of climate change and grazing intensity regime and suggests that appropriate adaptation strategies for maintaining the carbon storage function of Alberta's native grassland ecosystems may differ among regions, depending on the magnitude of climate change in each region.

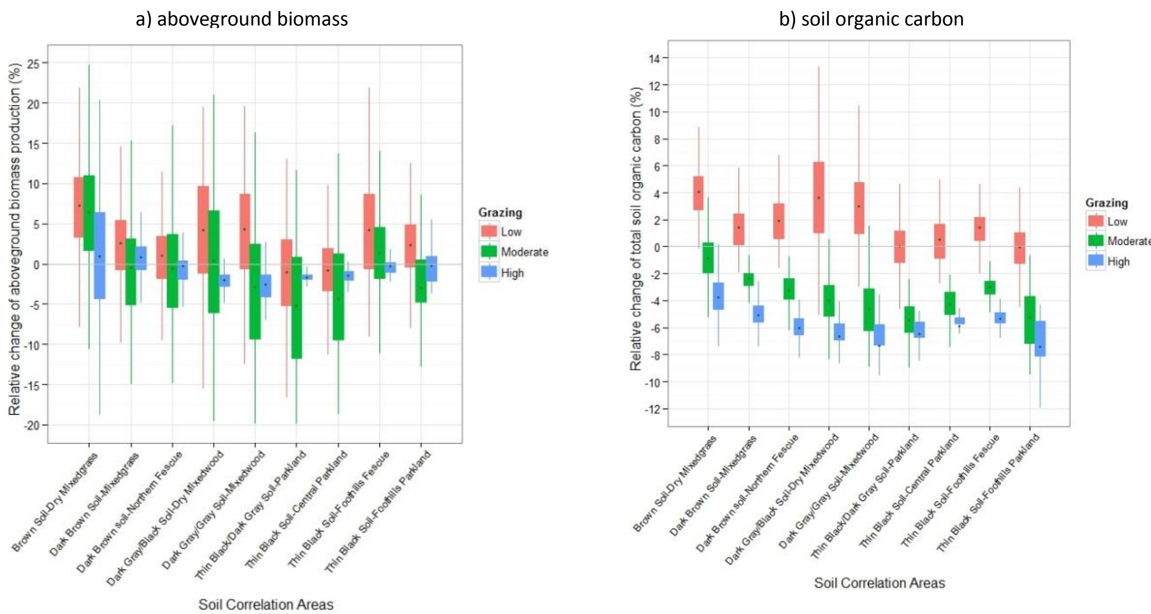

Figure 3. Change in a) aboveground biomass, and b) soil organic carbon (top 20 cm) in each of nine soil correlation areas between the periods 1960-1980 (1970s) and 1990-2010 (2000s) based on the CENTURY simulation model under low-, moderate-, and high-intensity grazing regimes. For grazing regime and SCA, mean values (point), middle quartiles (25%-75%; box) and maximum and minimum values (lines) are presented, representing the variation among AGRASID polygons within each SCA .

Effects of projected climate change and grazing regime on aboveground biomass

Projected changes in annual precipitation to the end of the century were smaller, relative to the variation within SCAs, than the projected changes in minimum and maximum temperatures (Fig. 4). By the end of the century, minimum and maximum temperatures were projected to warm by 4-7 °C, with the greatest warming projected for the minimum temperatures in the cooler SCAs in the northern part of the province.

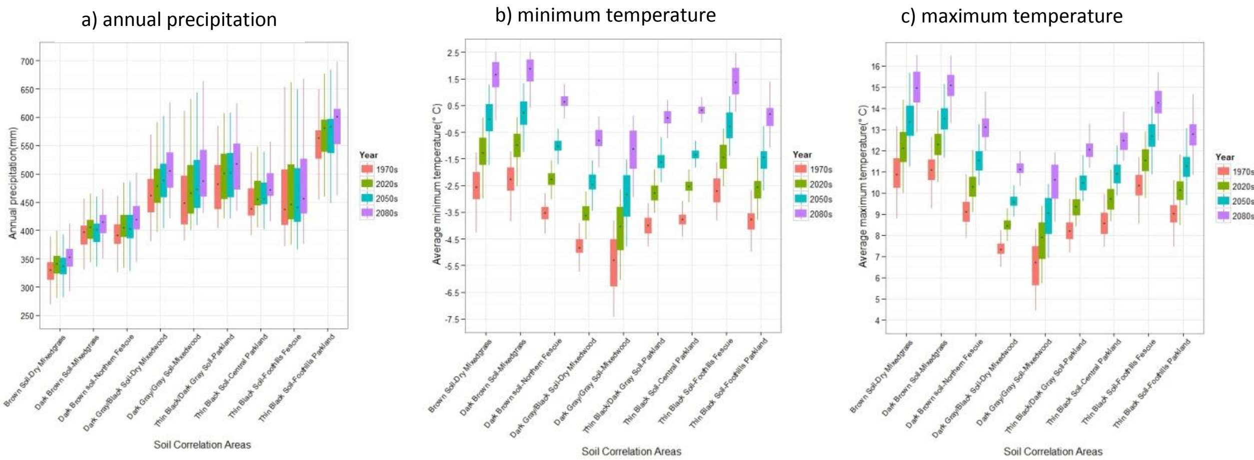

Figure 4. Historic (1961-1990) and projected (2020s: 2011-2040, 2050s: 2041-2070, and 2070s: 2071-2100) annual precipitation, and minimum and maximum temperature in each SCA. Mean values (points), middle quartiles (25%-75%; box) and maximum and minimum values (lines) are presented, representing the variation among AGRASID polygons within each SCA.

At the provincial scale, modeled patterns of relative change in aboveground biomass in response to projected changes in climate varied among grazing regimes (Fig. 5). Under low- and moderate-grazing intensities, AG biomass was predicted to increase relative to the 1961-1990 baseline over the short-and medium-term, with the greatest increases (approx. 20%) in the middle of the century. By the end of the century, AG biomass was predicted to return to baseline conditions (average relative change near 0%). Under high-grazing, the increase in AG biomass was predicted only for the 2020s, with a decline predicted by the 2080s of approx. 15%.

The average magnitude and range of changes in aboveground biomass predicted in response to future climate conditions (Fig. 5) far exceed those observed in response to recent climatic change(Fig. 3a), reflecting the magnitude of the projected changes in climate relative to observed recent change (Fig. 2, Fig. 4).

Among SCAs there was considerable variation in predicted changes in aboveground biomass in response to projected climate change and additional variation in the interaction among climate change and grazing regimes (Fig. 6). In SCAs in the northern part of the province (Mixedwood and Parkland), AG biomass was predicted to be stable or decline in response to future climate conditions, whereas in SCAs in the Mixedgrass and Fescue regions estimated AG biomass increased in response to climate change, especially over the short- and medium-terms (2020s and 2050s).High-intensity grazing was predicted to have a more negative or neutral impact on AG biomass across time periods when compared with low- or moderate-intensity grazing, except for in the near-term in the Mixedwood and Parkland SCAs, and in the long-term in the Dry Mixedgrass SCA. The spatial distribution of change in AG biomass in response to grazing in the 2020s, 2050s, and 2080s is presented in figure 7.

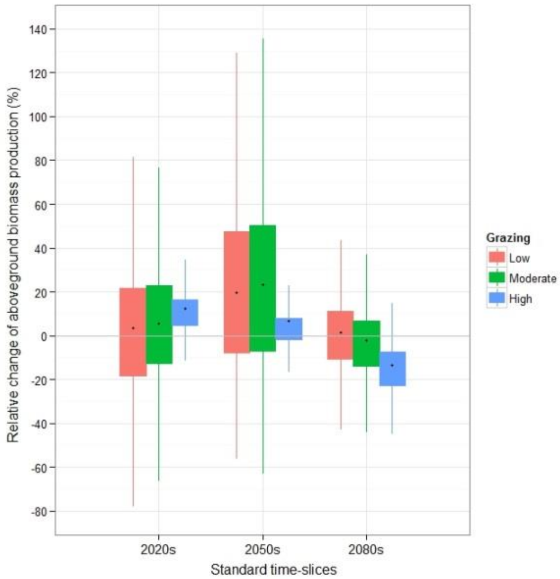

Figure 5. Provincial change in aboveground biomass production in response to projected future climate conditions in the 2020s (2011-2040), 2050s (2041-2070), and 2080s (2071-2100) based on the CENTURY simulation model under low-, moderate-, and high-intensity grazing regimes. For each grazing regime and time period, mean values (point), middle quartiles (25%-75%; box) and maximum and minimum values (lines) are presented, representing the variation among AGRASID polygons across Alberta.

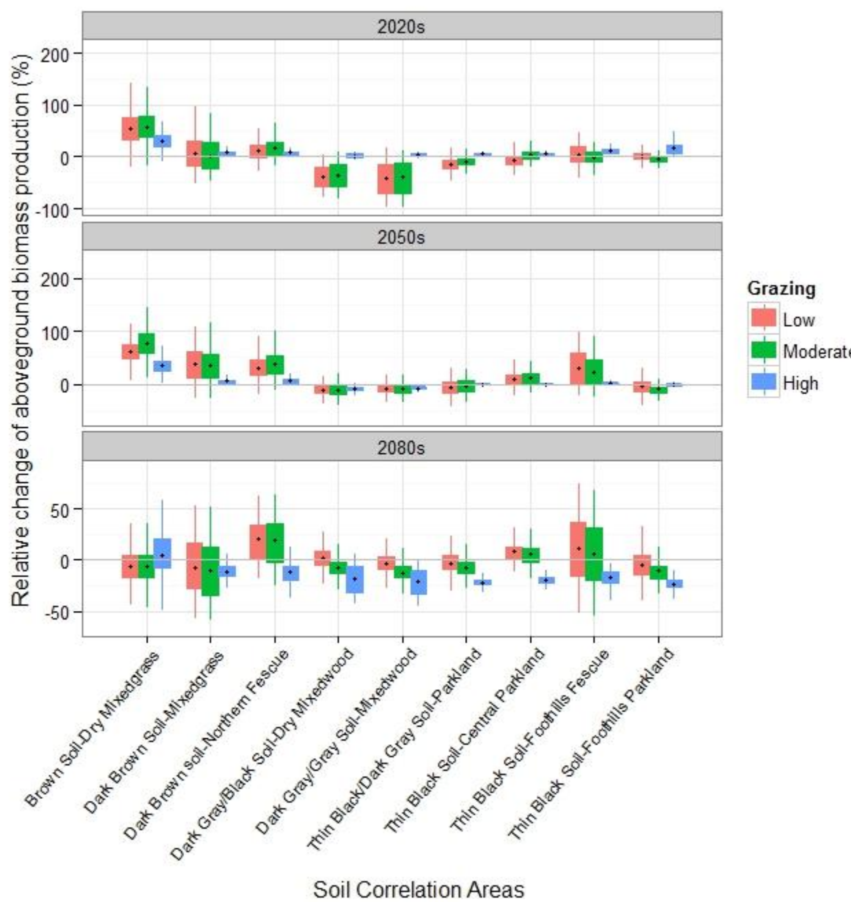

Figure 6. Change in aboveground biomass in each of nine soil correlation areas, in response to projected future climate conditions in the 2020s (2011-2040), 2050s (2041-2070), and 2080s (2071-2100) based on the CENTURY simulation model under low-, moderate-, and high-intensity grazing regimes. For each grazing regime and time period, mean values (point), middle quartiles (25%-75%; box) and maximum and minimum values (lines) are presented, representing the variation among AGRASID polygons within each SCA.

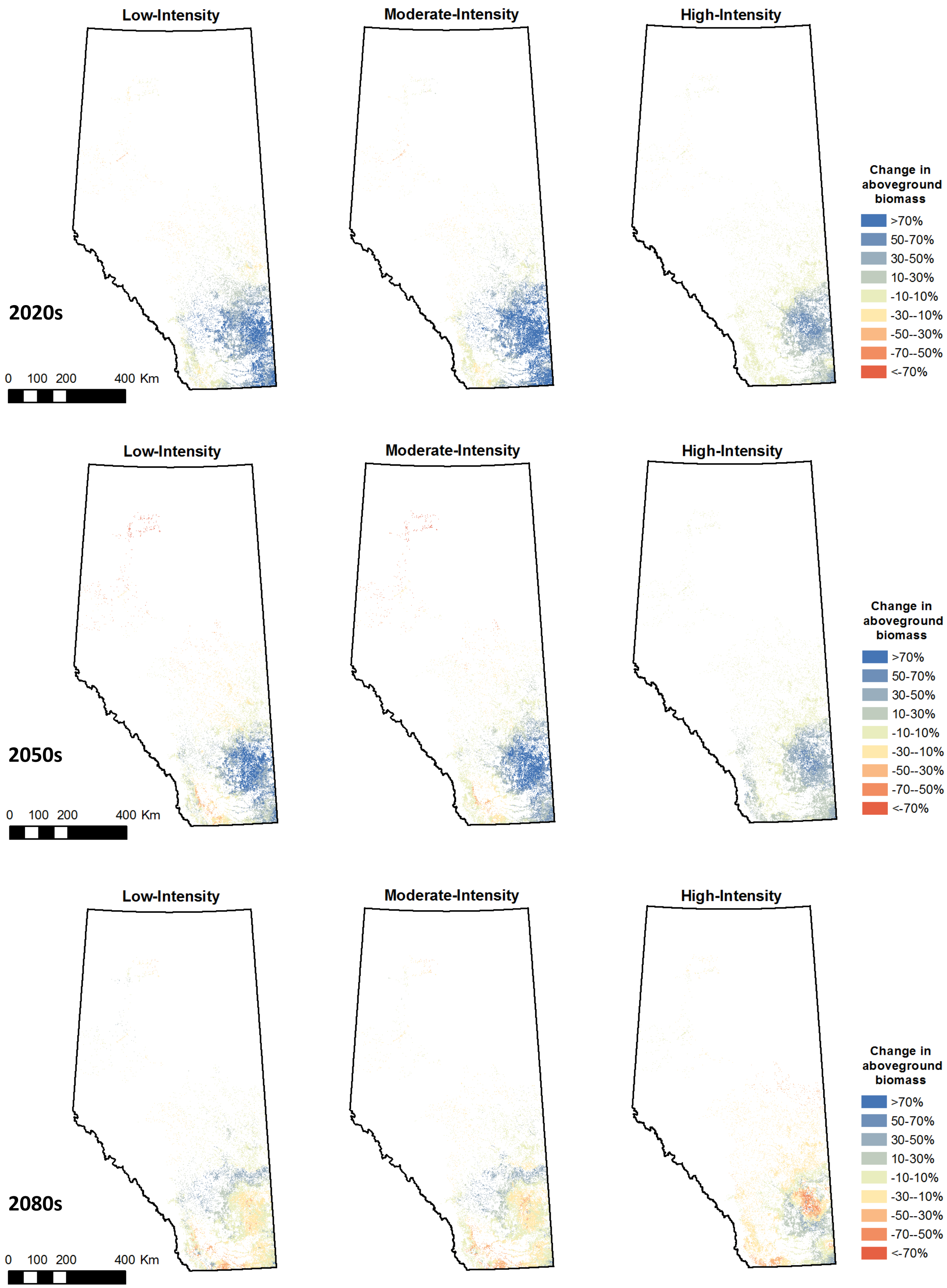

Figure 7. Changes in aboveground biomass between the historic period (1961-1990) and the 2020s (2011-2040), 2050s (2041-2070), and 2080s (2071-2100) in response to projected climate change and different levels of grazing intensity.

Implications

Our preliminary analysis of climate change impacts on the provision of rangeland carbon storage and aboveground biomass production demonstrated how climate change can be incorporated into the assessment of ES across the Alberta landscape, and how these ES models can be used to evaluate alternative potential climate change adaptation strategies. In particular, our initial analysis of aboveground biomass production and soil carbon storage in the top soil layers indicated several general trends:

> **1)** In response to recent warming and projected changes in climate, especially to the mid-century, modeled aboveground biomass and soil carbon storage increased or remained stable, indicating that the these processes may be enhanced by climate change over the medium-term. However, declines in both attributes were predicted by the end of the century.
>
> **2)** The modelled responses of AG biomass and SOC were sensitive to grazing intensity, with low-intensity grazing typically resulting in increases in both processes over recent years and in projected future conditions. This suggests that grazing management has the potential to be a useful adaptation measure to respond to the impacts of climate change on aboveground biomass production and carbon storage in rangelands soils. However, further analysis is required to translate these estimates of ecosystem processes to the associated ecosystem services of carbon sequestration and forage production.
>
> **3)** The response of rangeland AG biomass and SOC to recent and potential future climate change and grazing regime varied considerably among soil correlation areas, suggesting best management practices, climate change risks, and adaptive strategies to maintain the provision of these services under a changing climate will be region-specific.

Next Steps

Rangeland carbon storage and aboveground biomass production model refinements

We are continuing to work on calibration and validation of the CENTURY model for each of the nine SCAs. Further, we are pursuing the incorporation of climate change projections at finer temporal resolution to improve our projections of aboveground biomass and allow for examination of changes in soil carbon in response to future climate conditions. We also anticipate simulating additional grazing management scenarios, including different grazing systems (e.g., rotation) to determine their impacts on ecosystem service provision under current and future climate regimes.

Cost-benefit analysis of alternative climate change adaptation strategies

The monetary value of ecosystem services can be estimated in alternative ways, depending on the type of service and whether it relates to an existing market (de Groot et al. 2002). Additionally, different types of valuation are most appropriate depending on how the information will be used (e.g. for raising awareness versus assessing a specific land-use or policy scenario; Table 1 in Costanza et al. 2014). The total value of forage can be estimated using the replacement cost method (de Groot et al. 2002), which bases the value on how much it would cost to replace the forage produced on grasslands by supplementary green feed purchased on the market (e.g., $59.10/tonne, 2006-2010 average; Kosinski 2012). Similarly, the total value of soil organic carbon can be based on the price of carbon on an existing market (e.g., Alberta's $15/tonne price; Government of Alberta 2008). However, these total values only provide an understanding of the magnitude of the service, and are unsuitable for determining how a rancher's total income would change in response to altering cattle stocking rate; assessing this potential change in value is what is relevant to the decision-making context of whether implementing a lower stocking rate is an appropriate adaptation to climate change (Keeler et al. 2012; Costanza et al. 2014). Additionally, because grazing management decisions also influence the provision of these services in the future, it is critical to assess whether potential adaptation strategies will lead to rangelands that can provide a sustainable value to ranchers over the long-term.

Towards an integrated model of ecosystem services

A primary objective of ABMI's ESA project is to integrate models for a variety of ecosystem services across the Alberta landscape to support a better accounting of the value of multiple ES and potential trade-offs in land use and land management decisions. For example, lowering the cattle stocking rate may decrease a rancher's income, because forage production (via the sale of beef cattle) is the only ES that is currently valued in a functioning market. With markets for other ES, the loss of income due to reduced beef production could be offset through the value of other services that increase in response to lower stocking rates, such as soil carbon storage and water purification. An integrated model that estimates how multiple ES respond to a single management activity is critical to support a more complete cost-benefit analysis of potential climate change adaptation strategies.

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