SIMULATION OF THE EFFECTS
OF
CLIMATE CHANGE
ON
FORAGE AND CATTLE PRODUCTION
IN
SASKATCHEWAN

A Thesis Submitted to the College of

Graduate Studies and Research

in Partial Fulfillment of the Requirements

for the Degree of Doctorate of Philosophy

in the Department of Animal and Poultry Science

University of Saskatchewan

Saskatoon

By

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ABSTRACT

Multiple global climate models suggest that the Canadian Prairies will experience temperature increases due to climate warming. This could influence pasture and grazing production. Three climate scenarios CGCM2 A21, CSIROMk2 B11 and HadCM3 A21 were used to predict daily weather data to 2099 and incorporated into the GrassGro decision support tool to project pastoral production during 30-year increments, 2010 to 2099. Simulations were compared with the World Meterological Organization baseline years, 1961-1990 at two sites (Saskatoon and Melfort) and two soil textures (loam topsoil / loam subsoil and sandy-loam / sandy-clay-loam). Two tame grasses [crested wheatgrass (CWG; *Agropyron cristatum*) and hybrid bromegrass (HBG; *Bromus inermis x Bromus riparius*) and a mixed native pasture (*Festuca hallii; Elymus lanceolatus; Pascopyrum smithii; Nassella viridula*) were studied at each location.

Soil moisture was greater for loam/loam than sandy-loam/sandy-clay-loam resulting in more plant available moisture in all climate scenarios at both locations. However, plant available moisture alone was unable to explain changes in pasture dry matter (DM) production. The results projected from CGCM2 A21 were more favorable to plant and livestock production than those of CSIROMk2 B11 and HadCM3 A21. CGCM2 A21 simulated increases in mean DM production of HBG at both locations during spring each 30-yr period ($P<0.05$) but an overall decline ($P<0.05$) in mean average daily gain (ADG) of steers at Melfort, whereas at Saskatoon there was an increase in ADG ($P<0.05$). CWG decreased in DM production at Melfort during summer and increased at Saskatoon with CGCM2 A21 but there was an overall decrease in ADG of steers during each 30-yr period relative to baseline. It was concluded that HBG was better able to stabilize production under various future climatic conditions than CWG. There was a shift in species dominance from *Festuca hallii* to *Elymus lanceolatus* in the mixed native pasture at both locations associated with the increase in summer temperatures. This suggests that various grass species may respond differently to climate change.These results indicate that climate change will cause significant changes in soil moisture, productivity and quality of tame pastures, liveweight of grazing cattle and species composition of native pasture.

ACKNOWLEDGEMENTS

The author wishes to express her appreciation to Dr. R.D.H. Cohen, and Ms. Elaine Wheaton for their guidance and insight into this project. Appreciation is also extended to the rest of my committee (Dr. B. Laarveld, Dr. J.P. Stevens and Dr. D.W. Anderson) for their support and for reviewing the thesis material.

Finally, a special acknowledgement to my family for their patience, persistence and encouragement in helping me complete this project.

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LIST OF ABBREVIATIONS & ACROYNYMNS

Abbreviation	
ABA	Abscisic Acid
ADG	Average Daily Gains
AET	Actual Evapotranspiration
AGCM	Atmospheric Global Climate Model
AOGCM	Atmopheric-Ocean Global Climate Model
ASW	Available Soil Water
CCIS	Canadian Climate Impacts and Scenarios website
CERES	Crop Environment Resource Synthesis Model
CGCM2	Canadian Global Climate Model
CO2	Carbon Dioxide
CSIRO	Commonwealth Scientific and Industrial Research Organization
CWG	Crested Wheatgrass
DDM	Digestible Dry Matter
DM	Dry Matter
DMD	Dry Matter Digestibility
DMI	Dry Matter Intake
DST	Decision Support Tool
GCMs	Global Climate Models
GDP	Gross Domestic Product
GHG	Greenhouse Gases
HadCM3	Hadley Climate Model
HBG	Hybrid Bromegrass
LAM	Limited Area Models
LL	Loam Loam Soil Texture
Max T	Maximum Temperature
MEI	Metabolizable Energy Intake
MGAH	Mean Green Available Herbage
Min T	Minimum Temperature
MO	Month
MTAH	Mean Total Available Herbage
OGCM	Oceanic Global Climate Model
Pan E	Pan Evaporation
PET	Potential Evapotranspiration
Ppt	Precipitation
SD	Standard Deviation
SLSCL	Sandy-Loam / Sandy-Clay-Loam Soil Texture
SRES	Special Report on Emissions Scenarios
SWRRB	Simulator for Water Resources in Rural Basins
TE	Total Evaporation
WMO	World Meteorological Organization

CHAPTER 1

1.0 INTRODUCTION

1.1 Significance and Context

Agriculture is important to the economy of Saskatchewan. Climate has a major effect on production, ultimately determining the success of this industry. There is now indisputable evidence suggesting that the world's climate system is changing. Globally, present temperatures are warmer than any of the average temperatures recorded over the last millennium (IPCC 2001a). The increase during the 21st century is expected to be between 0.2 and 0.3 °C per decade (IPCC 2007). Zhang et al. (2000) reported increases in annual surface air temperatures (SAT) between 0.5 and 2.5 °C and ground surface temperature (GST) between 1.5 and 4 °C in the southern regions of the Canadian Prairies between 1950 and 1995. These are the largest changes in SAT and GST in the Northern Hemisphere (Zhang et al. 2000). The Northern Mixed Grassland region of the Great Plains of North America is at its northern boundary in Saskatchewan and the grasses in this region could be expected to be vulnerable to these effects of climate change.

It has been suggested that the Canadian Prairies can expect to be significantly warmer by the 2050s (Zhang, 2000; Shepherd and McGinn 2003). Limited research has been conducted to project the impact of these climatic changes on soil moisture, which ultimately drives plant production.

Wheaton (2001), using an early climate change model scenario (CGCM1), projected soil moisture to decrease during the summer. This initial work was based on the difference between precipitation and evaporation as the indicator of soil moisture. It was suggested that other variables are required to improve projections of the effect of climate change on soil moisture. Projections of increased summer temperatures, slight to no changes in precipitation and decreased soil moisture on the prairies suggests that grassland production should decline (Thorpe, 2004). If future climatic projections for the southern regions of Saskatchewan are similar to those predicted for areas in the Northern Great Plains of the United States with similar climatic regimes, a shift in vegetation species could also occur (Thorpe, 2004; Sauchyn, 2007). Baker et al. (1993), using the Simulation of Production and Utilization of Rangelands model (SPUR) projected decreased forage and cattle production would result from climate change in the central United States. Campbell and Stanford-Smith (2000) explored some of the uncertainties with respect to the prediction of changes to pasture and rangeland production and management implictions following climate change. Significant uncertainties still exist. There has been some advancement in the confidence with which the implictions on vegetation production can be predicted but there are still uncertainties regarding botanical compostion, forage quality and animal production. These uncertainties reduce the ability of pastoral producers and managers to plan for the future, leaving them vulnerable to the likely effects of climate change. Although there is information now available for intensive pastures in moist temperate regions of the world, little research has been reported for the semi-arid regions such as the Canadian Priaries.

The present thesis addresses some of the knowledge gaps that have been identified by the Global Change and Terrestrial Ecosystem (GCTE) Pastures and

Rangelands network (Campbell and Stanford-Smith, 2000). These include the need to study the impacts of climate change on a multivariate level involving climate, soils, plants and animals in a single computer simulation model. Predicting the future of any one of these factors in isolation is of little value since each is embedded within very complex systems that are difficult to separate. This study uses a single interactive decision support tool in combination with various climate change predictive models to project the responses of soils, pasture grasses and grazing cattle to climate change from 2010 to 2099 in Saskatchewan.

The thesis provides answers to the following specific questions:

1. How will climate change affect soil moisture at specific two sites in Saskatchewan on two soils of different textures?

2. What will be the likely responses of seeded pasture grasses and grazing cattle to various projected climate changes in Saskatchewan?

3. Will climate change alter the botanical composition of mixed native pasture associations in Saskatchewan?

CHAPTER 2

2.0 LITERATURE REVIEW

2.1 Climate and Climate Change

The World Meteorological Organization (WMO) classifies climate as a long-term average of various weather features such as temperature and precipitation. The WMO uses 30-year averages to define climatological “normals” which generally include precipitation, temperature and wind data. There is a natural variability in climate that is attributed to factors such as interactions between atmosphere and oceanic currents, snow and ice cover, and vegetation and surface water. Other long-term variability is related to radiation, the earth’s rotation and orbit, and the movement of land relative to the oceans. This climate variability, which is described as the variation in the mean state and other statistics of the climate on all temporal and spatial scales beyond that of individual weather events, such as standard deviations, the occurrence of extremes etc., sometimes gets confused with climate change resulting from anthropogenic influences on climate causing drastic changes to the function of cycles beyond natural fluctuation (IPCC, 2001a).

2.2 Regional Scale vs Global Climate Models

A climate model is a plausible representation of the future climate that has been constructed using the understanding of global/ regional systematic function with natural and anthropogenic changes to the physical processes in global climate system expressed through the use of mathematical models called GCMs (IPCC, 2001a). Regional climate is based on topography, vegetation, and bodies of water (Giorgi, 2006). Regional climate models do not have the capacity to encompass all the aspects that affect climate (e.g., oceanic and atmospheric global circulation patterns). However, they do address some of the smaller local scale features (elevation, small bodies of water, and vegetation) that are missed when using Global Climate Models (GCM). Both models analyze atmospheric patterns similarly with the same mathematics and physics however, the weight each variable has at a regional scale will be different from that used to run global climate models.

Most of the concerns pertaining to climate change are on a regional scale. The problem lies in linking the models in scale so analysis on a local scale is possible. It is widely acknowledged that the direct outputs of climate change simulation from GCMs are inadequate for assessing land surface impacts on regional scales (Wilby and Wigley, 2000). Recent research has focused on improving the resolution of GCMs by nesting high-resolution limited area models (LAM) within them to account for local topographic forcing factors (Caya et al., 1995; Giorgi et al., 1994). The most advanced computers and calculations are used in running GCMs therefore there is a subsequent high cost to developing these scenarios. However, the crude approximations provided by the current state of GCMs may represent the best available estimates of future climate change at the regional level at the moment due to the cost of running regional models.

2.3 Climate Models and Scenarios

Climate models have been developed by several organizations around the world. There are other types of scenarios developed such as temporal or spatial analogues; climate models based on weather generators. All models have their advantages or disadvantages to their use. In expressing the complexity of models, GCMs are the most advanced tools currently available for simulating the global changing climate. The GCM-based scenarios have advanced since their first use in the early 1980s when they encompassed an equilibrium-response with no ability to allow oceans to circulate in the model (Parry and Carter, 1998). The ability to include more of the complexitys from the global climate system into GCMs has been possible with the advancement of super computers and thefocusing of research in areas where knowledge gaps exist.

GCMs describe the behavior of four main variables (temperature, humidity, surface pressure, and wind) based on the physical conservation laws and the use of non-linear partial differential equations (Hengeveld, 2000). A unifying feature of all the current models is that they divided the atmosphere and depths of the ocean into a series of horizontal grids and vertical layers. Current models have 10-30 layers and grid size resolutions of 2.5-3 degrees (Hennessey, 2003; IPCC, 2001a). Once the size of the grids are set, the rate of change of the primary output variables (pressure, temperature, humidity, wind, cloud cover, soil moisture, precipitation and snow cover) is determined from the governing equations by integrating forward in discrete time steps (Carter et al., 1999; IPCC, 2001ab).

Special Report on Emissions Scenarios (SRES) is a collection of possible scenarios that are developed based on different combinations of future emissions, technological and economic developments such as increased population, decrease in gross domestic product (GDP) and slow advance of technology (Nakicenovic et al., 2000). The SRES scenarios cover a wide range of the main driving forces of future emissions, from demographic to technological and economic developments. The set of SRES emissions scenarios is based on an extensive assessment of the literature, six alternative modeling approaches, and an "open process" that solicited wide participation and feedback from many groups and individuals. SRES includes the range of emissions of all relevant species of greenhouse gases (GHGs) and sulfur; and their driving forces give a wide range of radiative forcings for the various compounds. All the SRES scenarios give a positive radiative forcing value for the well mixed greenhouse gases. These SRES scenarios are named A1, A2, B1, and B2 depending on which growth assumptions are used. A2 represents high emissions and B2 low emissions. The number after the scenario represents the ensemble members. The A2 and B1 markers should be used to establish the widest range of future outcomes (IPCC 2007).

2.4 Global Climate Models

2.4.1 Canadian Global Climate Model (1& 2)

The Canadian Global Climate Model 1 (CGCM1) is a first generation coupled general circulation (Boer et al., 2000; Flato et al., 2000; and Kharin and Zwiers, 2000). There have since been two newer generations to this model the CGCM2 (second generation) and CGCM3 (third generation). Current information regarding these models can be found on the Canadian Centre for Climate Modelling and Analysis website (http://www.cccma.ec.gc.ca). There were many improvements to the models from the first to the second generation including changes in the ocean mixing from a horizontal/vertical diffusion to a isopycnal/eddy stirring, sea-ice dynamics and ocean spinup and flux adjustments. However, according to Töyrä et al., 2005, the changes the CGCM1 did not improve the ability of the model to simulate temperature. The CGCM2 A21 had a low spatial correlation coefficient during all seasons and overestimated annual and seasonal precipitation. This is attributed to the CGCM2 model using a bucket model for hydrology (Manabe, 1969). The CGCM2 A21 climate change scenario was used in this study as the CGCM3 was not ready for use. Not all the climate variables were available for the CGCM3 model and little was known about its ability to simulate climate for the Canadian Prairies. In comparison with several other GCMs, this model forecasts the greatest temperature increase and the least precipitation increase for the Canadian Prairies.

2.4.2 Hadley Coupled Climate Model (HadCM3)

HadCM3 is a model compiled in the United Kingdom (Gordon et al., 2000). Barrow (in Henderson et al., 2002) concluded that in comparison to several other GCMs, the HadCM3 A21 climate change scenario predicts the least temperature increase and the greatest precipitation increase for the Canadian Prairies. HadCM3 best represents the magnitude and spatial patterns of annual and seasonal mean temperature for the Canadian Prairies (Töyrä et al., 2005).

2.4.3 Commonwealth Scientific and Industrial Research Organization (CSIRO)

The CSIROMk2 B11 is an Australian climate change scenario and has been termed by many climatologists as a “mid-range” forecast for the prairies in comparison to the Canadian and the United Kingdom models (IPCC, 2001a; Barrow, 2000). The CSIROMk2 B11 is a coupled (ocean, sea-ice and atmosphere) model. Each grid box is 625 x 325 km with 9 vertical layers and 21 ocean layers (Hennessy et al., 1998). Refer to Table 2.1 for further comparison between climate models and their attributes.

2.5 Baseline Climate Data

A common reference point for using different climate change scenarios in research studies at a specific location is termed a ‘Baseline’. The IPCC (2001) has outlined the guidelines to the importance of baseline use. The baseline describes the average conditions, temporal and spatial variability; is used for testing and calibrating variability for impact models; baselines are used for determining trends and cycles that are useful in integrating global climate models; the main significance is as a reference point for studies in future to compare models to (IPCC, 2007).

The most commonly used climatological baseline is a 30-year ‘normal’ period. The World Meterological Organization (WMO) has set standards in using baselines with a standard reference year range from 1961-1990 to ensure compatibility of comparison among impact studies (IPCC, 2001b). The end-year of 1990 in this data set is the year of the Kyoto agreement as this is the benchmark year against which all reductions in green house gasses (GHGs) will be compared. Furthermore, this is the time period that most countries have climatological data available as computer code on a daily time scale (IPCC, 2001a). In the context of the earth’s time scale, this baseline period represents a very small sampling timeframe. As understanding of the processes increases, this baseline may change to include more of the variability on a spatial and temporal scales with fluctuations in climate.

2.6 Concerns with Using Global Climate Models

Global climate models are the best method to evaluate global functioning of systems as a whole on earth (Grassl, 2000). When developing a model the greatest challenge is measuring and understanding how certain variables play a role in climate function. For GCMs, variables may be weighted differently at a global scale than at a regional scale therefore, the climate response may not be reflected properly using the large scale Global Climate Models on a regional level. These climate variables may include cloud cover, surface processes, wind, wave action, currents, and other greenhouse gases (Reichert et al., 2002). The second limitation to using global climate scenarios is the way that economic and social development and plant cover variables will cause different responses on a regional scale.

Another long-term challenge for climate change scenarios is the ability to include variability and extremes in future climate. Future climate scenarios developed on a regional scale using the Delta Method have the same variability as the observed baseline time series. Mearns et al., 2001 highlights this limitation to GCM scenarios suggesting that climate scenarios should represent future conditions accounting for human induced climate change and natural climate variability and scenarios are only an intermediate step towards this goal.

2.7 Decision Support Tools

A decision support tool (DST) is a mathematical model that attempts to predict the chain of events that occur in nature to assist the user with a management decision process. Using an appropriate DST will make it possible to integrate the effects of changing climate on the soil, plant and animal interfaces therefore providing the best available method for studying the effects of climate change on forage and livestock production. This integration of future climate models with an appropriate DST for the prediction of the production of forage and grazing cattle has not previously been attempted. The majority of past research has used general regression models (Thorpe, 2004) or models such as SPUR, STEEPE + SOIL or Century (Baker et al., 1993; Bolortsetseg and Tuvaansuren, 1996; Schimel et al., 1991; Parton et al., 1996; Ojima et al., 1996). These models specialize in animal, soil and plant processes, however do not offer the same ability to evaluate the climate-soil-plant-animal ecosystem concurrently as does the GrassGro DST.together.

2.7.1 The GrassGro DST

GrassGro (Moore et al., 1997) is a daily time-step simulation model that uses a menu-driven interface within the Microsoft Windows operating system. Simulated pastures can consist of one or more species. Within each species, the biomass is divided into live, standing dead and litter material, and further split into digestibility classes. Seed and seedling dynamics are only modeled for annual species, while leaf and stem fractions of the shoot are distinguished in herbs (including legumes) but not in grasses. The model is driven by daily weather data [precipitation (rain/snow), maximum and minimum temperature, Potential Evaporation (PE) and radiation]. PE is computed from pan evaporation or, if PE is not available, the GrassGro software provides two alternative methods for estimating the potential ET values:

(i) PET = constant x (pan evaporation); (ii) the function used by the CERES crop model, which depends upon radiation and temperature. If radiation data are not available they can be computed from sunshine hours or from temperature and the coordinates of latitude and longitude. The model consists of a soil moisture budget in a profile divided into a user-defined topsoil/subsoil boundary and is constrained by the maximum rooting depth of the plant species.

Some pastures consist of a number of populations of different species or cultivars. Four distinct plant types are recognized on the basis of their morphology and ecology delineated by perennial and annual grasses and herbs (including legumes). Phenology is modeled by following each species through a number of developmental stages. Some plants have a vernalization requirement and this is modeled using a simplification of the vernalization index of Hochman (1987). After vernalization, the plant enters the vegetative stage. Transition from the vegetative to reproductive stage may be controlled either by day-length or by thermal time; a degree-day (DD) count. In perennials, the reproductive stage is ended by a combination of elapsed DD and threshold available soil water (ASW). Perennial grasses can exhibit a period of dormancy after reproduction finishes. In annuals, a senescent phenostage follows reproduction until a germination event occurs and the developmental cycle restarts. Net primary production on each day is governed by radiation, light interception (where plants can compete), temperature and soil water (either lack or excess can reduce growth). Allocation of primary production depends on the phenological stage (more goes to shoots in the vegetative stage and more to the flower and seed in the reproductive stage) and on the current ratio of root to shoot biomass. Death rates of live biomass depend mainly on whether the end of the growing season has been reached. However, frost mortality of live herbage does occur as a sigmoidal function of temperature and each frost is considered to "harden" surviving material so that a more severe frost is required subsequently for the same level of mortality. Standing dead biomass falls to the ground and becomes litter. The specific rate of fall of standing dead into the litter pool is modeled as a function of trampling and rainfall. Trampling is measured by the input variable "Stocking Rate" (SR). Digestibility changes are governed by temperature and moisture and are modeled with separate equations for green, standing dead and litter. Dry conditions accelerate the maturation of live material, but slow the loss of digestibility of standing dead and litter. Seeds and seedlings are simulated only in annual species. Embryo dormancy, induced seed dormancy (e.g., "hard seeds") and enforced seed dormancy are all modeled. Germination depends on surface soil moisture and temperature. Germinating seedlings are modeled separately, and can succumb to moisture stress and/or competition from established plants. Assimilation by seedlings is computed separately from assimilation by established plants because they are competitively inferior for light, have a smaller rooting depth and are more susceptible to death from stress. An establishment index is computed based on root/shoot biomass such that when the seedling root reaches a determined depth, establishment is considered complete and the seedling biomass is placed in the 80 % digestible live-mass pool and phenological development, consumption by grazers, etc., is restarted. Consumption and assimilation of herbage by grazers and their subsequent production of liveweight, fetus, milk, and conceptus is computed from the GrazPlan© animal biology model (Donnelly et al., 1997) which is also used in the GrazFeed© decision support system (DSS) as described by Freer et al., (1997). Animals are described by species, breed and "standard reference weight".

The animal’s intake is estimated as a fraction of their "potential" intake. Potential intake is the amount that animals would eat on abundant, high-quality pasture. It is largely a function of animal breed and age, with lactating animals having higher potential intakes than non-lactating animals. Actual intake is then determined by considering the amount and quality of pasture available to the stock. Animals select a diet of higher quality than that which is relatively abundant, and the effect of substitution of supplement for pasture is also taken into account. In addition, a deficiency of rumen-degradable protein will decrease intake below its potential. These factors are accounted for in the model.

Utilization of protein depends on the amount of apparently digestible protein leaving the stomach, which includes “bypass” protein and microbial crude protein. Maintenance requirements for energy and protein are estimated from the breed and weight of the animal, its level of intake and the steepness of the land about which it moves. Pregnancy and lactation requirements depend on how much energy and protein remains after maintenance requirements are met (or the extent of a deficit), and on the stage of pregnancy and/or lactation. Once all other uses of energy and protein have been estimated, the balance is used to estimate the weight change of the livestock. The energy and protein content of weight change varies with the age of the animals.

Parameterization for specific plant species in any integrated model is time consuming and very resource limited. Both native and tame grass species, and legume species, have been parameterized for use in the GrassGro DST on the Canadian Prairies (Cohen et al., 1995; Meyers, 1999; German, 1999; Cohen et al., 2003; Thompson, 2003).

2.7.2 Assumptions and limitations to GrassGro DST

GrassGro DST does have some limitations. One is the inability to predict the direct plant production response to increased CO_2. The potential responses to plant production are considered in section 2.9. The present version of GrassGro does not incorporate below ground nutrient cycling and uses a generalized soil fertility scalar of zero to one. A future version of GrassGro that is currently being compiled to incorporate below ground cycling of N, P, K and S. GrassGro is also unable to predict the affects of climate change on pests and diseases of plants and animals. Potential affects climate change on pests and diseases are refered to in section 2.12.

2.7.3 MetAccess and developing future climate scenarios

A weather compiler is a key component of a decision support tool designed to intergrate the soil – plant – animal interface because of the importance of weather on soil moisture and plant growth. The integration of a weather compiler to a soil - plant - animal model allows these interfaces to be examined. Climate data are entered into GrassGro via the weather compiler MetAccess (Donnelly et al., 1997). MetAccess compiles daily weather data (maximum and minimum temperature, rain, snow, radiation, evaporation, wind and various events such as dust, fog, hail, gale-force winds) into a format that can be read by GrassGro and it will accept these data from any source that can be downloaded in MS Excel format. MetAccess therefore can provide the important link between GCMs and GrassGro.

Early GCMs provided only monthly means for climate change data but more recent GCMs are providing monthly and daily values. Since plants react to daily fluctuations in climate and since GrassGro requires a daily time step of climate it is necessary to re-compile GCM output data into a daily time step.

2.8 Temperate Forage Plant Sensitivity to Climate Change

An expected change in diel temperature is the increase in night temperatures that may cause increased respiration resulting in reduced yield potentials (Rosenzweig and Hillel, 1998). Lundegardh, more than 50 years ago, stated that high night-time temperatures would cause injurious effects from the over use of photosynthate during respiration resulting in a decrease in yield (Frantz et al., 2004). For the past 30 years, research on the impacts of high temperatures on plant chemical processes has been ongoing. The main focus has been on the activity of enzymes and the changes made to membrane integrity (Frantz et al., 2004). Crafts-Brander and Salvucci (2002) reported that basic physiological processes, such as dark respiration and photosynthesis, are affected directly by temperature. The maximum rate of photosynthesis in temperate (C3) plants occurs at 20 to 30^{o}C in most temperate zones (Berry and Björkman 1980, Crafts-Brander and Salvucci, 2002).

The IPCC (2001b) suggested that the rise in temperature will extend the length of growing season allowing many species to extend northward as well as many species to mature earlier. However, inhibitions to plant physiological processes due to high temperature have also been documented (Raison et al., 1980). High temperatures disrupt the membrane structure of the plant by denaturing proteins and inhibiting the photosynthesis processes (Alexandrov, 1977; Armond et al., 1978; Schreiber and Berry, 1977; Berry and Björkman, 1980; Sharkey, 2000). High temperature also affects plant reproduction (Rao et al., 1992) causing decreases in seed production. When temperatures exceed the optimal for biological process, plants often respond negatively with steep drops in net growth and yield (Rosenzweig and Hillel, 1998). Not all species of plants are expected to have identical reactions to climate change because there is considerable genetic diversity and hence physiological diversity within the temperate species of plants.

2.9 Increased Atmospheric Carbon and Response of Plant Species

Plant production can be affected by many factors including that of carbon dioxide enrichment, temperature, and available moisture. Increased carbon dioxide has been sometimes refered to as the "fertilization effect" on plants because of its effect on increasing yield and reducing water use. Increased rates of net photosynthesis were found with increased CO_2 however increased temperature reduced stomatal diameter (Kobiljski and Dencic 2001). Partial stomatal closure leads to reduced transpiration per unit leaf area and, together with enhanced photosynthesis, often improves water use efficiency. Many early studies determining the effect of CO_2 enrichment on plant productivity show increases in production (Thomas and Hill, 1949; Gaastra, 1959; Kramer, 1981). However, recent studies incorporating long-term data show an initial rise in production declining after a few years. The quality of the forage grown under enriched CO_2 decreases and this effect is referred to as dilution. Owensby et al., (1996) showed that under enriched CO_2 plants matured faster and reduced the quality of forage available to grazing animals. For CO_2 enriched plants, the ratio of C:N increased (Newton, 1991) leading to a reduced digestibility and conversion efficiency of ingested forage to ruminant growth and reproduction (Huston and Pinchak, 1991). Reduced nitrogen concentration will increase fibre and reduce ruminant intake of forages (Owensby et al., 1996). Thomas and Harvey (1983) reported that leaves of plants under elevated CO_2 can have more waxes and extra layers of epidermal cells that may further reduce forage quality for ruminants.

2.10 Plant Available Water

The two most critical pathways for water flow through the soil-plant-atmosphere continuum are the soil-root and the leaf-air interfaces. The quality and digestibility of forages under grazing conditions are affected by the availability of water sources and nutrients. If water is not available photosynthesis is restricted, abscisic acid (ABA) hormones are released signaling the plant to close stomata and produce more lignin to protect the plant from the elements (Warren et al., 2007). The conservation adjustments made by the plant in response to reduced water availability and access to nutrients is reflected in reduced digestibility of the forage (Owensby et al., 1996).

Most climate change scenarios for the prairies show an increase in temperature and reductions in summer precipitation with a doubling of atmospheric carbon dioxide. Although the hydrological cycle for the globe is accelerating not all areas of the world will receive more precipitation. On the prairies some models indicate a small increase in precipitation (HadCM3 A21) while others predict a small decrease (CSIROMK2 B11). This small increase in precipitation may not increase soil moisture because the increased temperature may result in greater evaporation (Li et al., 2007). In addition, not all parts of the prairies may experience the same effects due to timing and intensity of rain events.

2.11 Effects of Climate on Forage Quality

Plants intercept sunlight and use the energy they capture to manufacture sugars from CO_2 in the air (Osmond et al., 1987). The sugars are used primarily for growth, but are also stored in plant cells. Generally, as a pasture becomes leafy it intercepts more sunlight and the growth rate of the pasture (kg DM ha^{-1} d^{-1}) increases. However, a point is reached when the capture of sunlight is saturated. At this point the pasture has the potential to grow at its maximum rate (Simpson and Culvenor, 1987).

The accumulation of responses listed in the above sections indicates that many of the processes during a plant's life cycle may be affected by climate change. These changes to morphology and chemical composition lead to changes in forage quality. The main determinants of forage quality are protein content and digestibility. Based on the sequence of events that can happen to plants in response to climate change on the Canadian Prairies dietary deficiencies of essential nutrients for herbivores is an increased possibility (Bremer et al., 1996). Ruminants rely on a complex community of microbial organisms living in concert to digest plant products and produce sufficient amounts of end-products to sustain growth. If the microbial ecology is altered by an imbalance of nitrogen, the growth of various pertinent species of organisms may be lost or reduced (Newton, 1991). Nutrient deficiencies, such as low protein in the forage, will reduce digestibility, and therefore rate of passage of forages through the rumen, due to a reduction in microbial activity. These repercussions reduce both the amount and rate of forage being digested by the animal (Owensby et al., 1996). Therefore the reduction in N concentration in the leaves and increased cell protection by higher quantities of fibrous and chemical components in response to climate change could reduce ruminant intake and assimilation. Owensby et al., (1996) suggests this could lead to reduction in growth and reproduction in grazing animals.

2.12 Response of Cattle to Climate Change

Dwyer (1961) reported a negative linear relationship between grazing time and average day-time temperature, and indicated that there was not an increase in night-time grazing to compensate for reduced day-time grazing. An increase in temperature could therefore reduce cattle productivity in terms of both growth and reproduction. However, this is likely to be less serious in the temperate areas of the world than in the tropical and sub-tropical areas.

The link between climatic change and infectious diseases in animals is complex but has shown to follow a general agent-host-vector transmission which can exclude any one of the transfers depending on the particular infectious disease cycle (Longstreth, 1989). Temperature, rainfall, and humidity are the major climatic factors driving vector transmission (IPCC 2001a). Most agent organisms do not have internal temperature regulation therefore, increasing their sensitivity to temperature. The potential effects of climate change on infectious diseases can target the host, agents, vectors and the ecosystem. Temperature can influence the reproduction (Reeves et al., 1994) and maturation rates of the infective agent within the vector organism (Kramer et al., 1983; Watts et al., 1987), as well as the contact and survival rates within the host animal (IPCC 2001a). Rainfall and water availability can provide a medium for rapid transfer to hosts as well as increase the geographical distribution of infectious disease. Environmental changes may directly increase exposure to infectious agents (e.g. anthrax) or indirectly increase disease transmission by expanding vector habitats. Altered or fluctuating ecological conditions have resulted in a marked increase in infection rates and associated diseases of many infectious organisms, including endo- and eco- parasites. Although there is some suggestion that climate change has played a role in the recent resurgence of infectious diseases further research is needed to determine the direct relationship with cattle on the Canadian Prairies. This is outside the scope of this study.

Table 2.1 Comparison of global climate models.

GCM	CGCM1	CGCM2	HadCM2	HadCM3	CSIROMk2b11
GCM Type	Spectral T32	Spectral T32	Finite Grid		Spectral R21
AGCM resolution °lat×°long	3.75×3.75	3.75×3.75	2.5×3.75	2.5×3.75	3.2×5.6
AOGCM number of vertical levels	10	10	19	19	9
Global grid: number of lat×long boxes	48×96	48×96	73×96	73 x 96	64×54
Canadian window: number of lat×long boxes	13×35	13×35	20×35	N/A	15×24
OGCM resolution °lat×°long	1.8×1.8	1.8×1.8	2.5×3.75	1.25 x 1.25	3.2×5.6
OGCM number of vertical levels	29	29	20	20	21
Warming (°C) at CO_2 doubling	2.7	N/A	1.7	N/A	2.0

(adopted from http://www.cics.uvic.ca/scenarios)

N/A- Not Available

AOGCM-Atmospheric-Ocean Global Climate Model

AGCM- Atmospheric Global Cliamte Model

OGCM- Oceanic Global Climate Model

CHAPTER 3

3.0 SIMULATION OF SOIL MOISTURE AND EVAPORATION AT TWO LOCATIONS IN SASKATCHEWAN, CANADA USING THREE GLOBAL CLIMATE SCENARIOS

Soil moisture is vital to the agricultural and ranching industries on the Canadian Prairies. Recent changes to Canadian Prairie temperatures and precipitation have already had discernible impacts on agricultural production (Cutforth et al., 1999; Williams et al., 1988). In recent years, early frosts, flooding and consecutive drought years have affected production (http://adaptation.nrcan.gc.ca/index_e.php). The effects of changing climate on hydrologic systems will become an increasing issue in semi-arid regions such as Saskatchewan because the risk of droughts is expected to increase into the future (Li et al., 2007; Scott and Suffling 2000).

Few studies have examined the effects of climate change on a regional scale in Canada (Bonsal et al., 2001; Clark et al., 2000; Töyrä et al., 2005). Many of the past studies have analyzed the effects of climate change only in terms of annual temperature and precipitation (Arthur and Abizadeh 1988). Recent research has suggested that climate change may not fluctuate the annual mean temperature and precipitation as much as the seasonal distribution of these parameters (Akinremi et al., 2001). Moreover, the changes are likely seen not only seasonally, but the amplitude of higher temperatures found is likely to be reflected in higher minimum temperatures rather than maximum temperatures on the prairies (Bonsal et al., 2001; Zhang et al., 2000). With higher minimum and/or maximum temperatures, evaporative demands are expected to increase that may cause general decreases to soil moisture if precipitation declines (Robock et al., 2000, Manabe et al., 2004 and Wang and Wang, 2007). These responses may be highly region and season specific making studying the effects challenging. The effect of future climate change on soil moisture have not been extensively studied on the Canadian Prairies (Wheaton, 2001; Shepherd and McGinn, 2003).

GrassGro (Moore et al., 1997) is a decision support tool that is designed to help ranchers make decisions regarding forage production, and animal (sheep or cattle) production based on site-specific climate data. The abiotic inputs required for GrassGro are solar radiation, maximum and minimum air temperature, precipitation, potential evapotranspiration (PET), estimated as 80% of the pan evaporation, and day length. This latter input is computed from the latitude and day of year with equations reported by Strapper (1984) as described by Moore et al. (1997). A climate compiler, MetAccess (Donnelly et al., 1997) is used by GrassGro to incorporate daily climate data from historical and future climate predictions. These data can be used by the GrassGro DST to predict soil moisture (Moore et al., 1997). GrassGro has an integrated soil moisture submodel modified from the SWRRB (Simulator for Water Resources in Rural Basins) model of Williams et al. (1985). Soil evaporation occurs from the first layer until its relative water content is less than or equal to that of the second layer. Excess demand for soil evaporation is then removed in such a way that the decline in the relative content of the two upper layers is the same (Moore et al., 1997). Once the soil moisture budget for the day has been completed, the actual soil water values are re-computed for use in the plant growth model. Wind influences potential evaporation by increasing evaporation from the soil surface when moisture is present. The ability to simulate soil moisture in a decision support tool such as GrassGro makes it possible to use various global climate models to predict the effects of climate change on site-specific soil moisture budgets.

The objective of this initial study was to use GrassGro and its climate compiler MetAccess to:

1) highlight the changes in climate projected by GCM scenarios developed in Canada (CGCM2 A21), United Kingdom (Had CM3 A21), and Australia (CSIROMk2 B11) during a future 30 year time period of 2040-2069 with data recorded during a baseline time period of 30 years (1961-1990) at two locations in Saskatchewan (Saskatoon and Melfort);

2) use GrassGro to determine the change in soil moisture during the 2040-2069 future period from the baseline time period under a continuous perennial forage cover of Crested Wheatgrass (*Agropyron cristatum*).

3.1 Methodology

3.1.1 Observed weather data

Recorded baseline daily weather data (1961-1990) for Saskatoon (52 º 10’N 106 º 41’ W, elevation 501 m) and Melfort (52 º 49’N 104 º 36’ W, elevation 480 m) for maximum and minimum air temperature; precipitation (rain and snow); solar radiation and pan evaporation were obtained from records kept by Saskatchewan Research Council at Saskatoon and Agriculture and Agri-Food Canada Research Station at Melfort. Wind speed was downloaded from the Environment Canada’s website: http://climate.weatheroffice.ec.gc.ca/climateData/canada_e.html. These data were downloaded into MetAccess to be used by GrassGro to predict soil moisture and total evaporation. Mean annual data for both locations are given in Table 3.1. The annual total precipitation (rainfall equivalents) for 1961-1990, 2010-2039, 2040-2069 and 2070-2099 is shown in the Appendix.

3.1.2 GrassGro

GrassGro has four integrated models, a weather model (MetAccess, Donnelly et al., 1997), an animal model (Grazfeed, Freer et al., 1997), and plant and economic models (Moore et al., 1997). GrassGro has been used in Australia (Donnelly et al., 1998; Donnelly et al., 2002), Canada, (Cohen et al., 2003; Cohen et al., 2004a; Lynch et al., 2005; Perillat et al., 2004) and China (Xin et al., 2002). GrassGro is a unique DST that can be used to investigate the physiological response of individual pasture species and livestock production at specific locations (Cohen et al., 2003).

3.2.3 MetAccess

MetAccess (Donnelly et al., 1997) is a weather compiler designed to analyze and summarize long-term weather data. Weather data can be imported and stored in a MetAccess file by location based on latitude, longitude and elevation. Historical MetAccess weather files were created for 1961-1990 at two locations and files were created for 100 years of future climate data adapted from each of three GCM scenarios, CGCM2 A21, HadCM3 A21 and CSIROMk2 B11. Any missing pan evaporation data were estimated using the Crop Environment Resource Synthesis model (CERES), which predicts pan evaporation from radiation and temperature (Ritchie, 1972; Meyer et al., 1999).

3.2.4 Climate Scenarios

Three global climate models were chosen to produce a range of potential climate change scenarios as recommendation by the Intergovernmental Panel of Climate Change (IPCC, 2001a). The three GCMs were the Canadian Climate Centre Model (CGCM2) A21 of the second generation (3.75 x 3.75° resolution grid about 400 km) (Flato and Boer, 2001); Hadley Climate Model (HadCM3) A21of the third generation (2.5 x 3.75°) (Gordon et al., 2000; Pope et al., 2000) and Commonwealth Scientific and Industrial Research Organization (CSIROMk2 B11; 5.6 x 3.2°) (Hirst et al., 1996; Hirst et al., 2000). HadCM3 A21 and CSIROMk2 B11were chosen because of their ability to represent greenhouse signals (Hengeveld, 2000), replicate the magnitude and spatial patterns of precipitation and air temperature (Töyrä et al., 2005) and provide representation of climatic systems on the Canadian prairies (Wheaton, 2001). The Canadian Climate Impacts and Scenarios website (CCIS) (www.cics.uvic.ca/scenarios/index.cgi) provided the future change fields via the Delta Method for the three climate models used in this study.

The monthly change fields were applied to the 1961-1990 recorded daily data during each month for the future time periods of 2010-2039, 2040-2069 and 2070-2099. The new daily minimum and maximum temperature, wind and solar radiation data were calculated by adding the monthly change fields to the recorded data during 1961-1990 at each location. Solar radiation differences are provided by the CCIS website in W m^{-2}. These data were converted to MJ as required by MetAccess using W= 0.0864MJ d^{-1}. Future precipitation in the climate models is based on a percent difference from a baseline. This was the only climate parameter to use percent rather than a direct difference. The monthly change fields for each of the climate scenarios were multiplied by the historic recorded daily data to generate new future daily precipitation data. The nearest grid point to the location was used. In some cases the spatial scales of the climate models resulted in the same grid point changes applied to two ecologically different sites (Saskatoon and Melfort). A program (Weather Importer) was created to allow easier importing of the large excel strings (1961-2099) of daily climate data into MetAccess.

Table 3.1 Mean annual climate data 1961-1990 for Melfort and Saskatoon.

	Location	
Attribute	**Melfort**	**Saskatoon**
Rainfall (mm)	290.4	253.8
Total Precipitation (mm)	402.5	347.2
Daily Maximum (^{o}C)	6.3	8.0
Daily Minimum (^{o}C)	-4.8	-4.0
Wind (m/s)	4.7	4.4
Radiation (MJ m^{-2})	12.46	13.84
Pan Evaporation (mm)	1005	1199

Table 3.2 Soil Characteristics used in the GrassGro simulations.

Variable	**Values**	
Soil Texture (Topsoil/Subsoil)	Loam/ Loam	Sandy loam / SandyClayLoam
Topsoil depth (mm)	280	280
Topsoil field capacity (%)	26	21
Topsoil wilting point (%)	13	11
Topsoil initial water content (%)	14	14
Topsoil Bulk Density (g/cm^3)	1.4	1.5
Subsoil depth (mm)	1220	1220
Subsoil field capacity (%)	26	25
Subsoil wilting point (%)	13	16
Subsoil initial water content	19	28
Subsoil Bulk Density g/cm^3	1.4	1.4
Soil evaporation potential	4.5	3.5
Fertility Scalar	0.8	0.8

3.2.5 Soil Texture and Soil Moisture

GrassGro allows the user to choose any soil texture from sand to heavy clay and provides the user with default average bulk densities for each or the user may enter the exact bulk density if it is known. For this study two soil textures were used to simulate soil moisture at both locations; a coarse textured soil with sandy loam (SL) topsoil and a sandy clay loam (SCL) subsoil and a finer soil texture with loam (L) topsoil and loam (L) subsoil. Details of the soil parameters used are given in Table 3.2. GrassGro reports volumetric soil moisture in eleven soil layers and the layers are determined based on total depth of the soil profile. During this simulation study, both sites were set to the same soil depth of 1220 mm. For this study, moisture was reported at two depths, 0-140 mm and 430-580 mm; the latter being more representative of changes in long-term moisture levels.

GrassGro determines soil moisture based on the Simulator of Water Resources in Rural Basins (SWRRB) model of Williams et al. (1985). The soil adaptation equations were tailored for a continuous sward rather than a row crop. The specific soil moisture budget equations used by GrassGro are reported in Moore et al. (1997). Soil layer boundaries are set at 15mm to model water availability at the seeding depth and maximum rooting depth of the pasture spescies. There are two submodels (charging and evaporation) that make up the soil moisture budget. The charging submodel includes interception of precipitation by the sward using equations from Parton (1978). Surface runoff is calculated using the USDA Soil Conservation Service runoff equation. Excess rainfall over interception and runoff is placed in the surface water store, and percolation of water from each layer to the next lower layer is simulated using the calculations reported by Williams et al (1985). The Evaporation submodel uses calculations by Richie (1972). Evaporation is first taken from standing water on the surface then evaporative demand is met by the soil and transpiration in parallel. Once the soil moisture budget for the day has been completed, the available soil water (ASW) values for each soil layer are re-calculated for use in the plant growth model. GrassGro simulates volumetric soil moisture data (the volume of water to the volume of soil).

3.2.6 Experimental Procedures

3.2.6.1 Validation and adjustment of CERES predicted pan evaporation

To check the validity of pan evaporation (Pan E) data generated from CERES, these data (X) were compared with data recorded at Melfort and Saskatoon from April 1 - October 31, 1961-1990 (Y) using Student's paired 't' test and regression.

3.2.7 GrassGro Simulations

Simulations used observed climate data sets from Saskatoon and Melfort for the time period 1961-1990 (baseline data) and data for maximum temperature (Max T), minimum temperature (Min T), total precipitation as rainfall equivalents (Ppt) and soil moisture at two layers (0-140 mm; 430-580 mm) were compared with data generated from three climate change scenarios for the 2040-2069 time period.

Crested wheatgrass (*Agropyron cristatum*) was assumed to be the vegetation cover as it is a widely used forage species in Saskatchewan. A programmed removal of the standing crop every fall (November 30) was included to allow effective use of light and moisture for new growth which would be impeded by the large build up of dead herbage and litter if it was not removed.

3.3 Results and Discussion

3.3.1 Validation and Adjustment of CERES Predicted Pan Evaporation

CERES data for predicted mean total monthly Pan evaporation (Pan E) were different ($P < 0.001$) from recorded data at both locations (Melfort 95.95 ± 2.67 v 134.09 ± 3.50 and Saskatoon 108.21 ± 2.86 v 157.64 ± 3.77 mm mo-1 respectively). This necessitated an adjustment of CERES data for these locations to more accurately reflect recorded Pan E. This was done by regressing recorded data (Y) on CERES predicted data (X) for each location (Figure 3.1) as follows:

Melfort: $Y = 11.72 + 1.275 X$ ($R2 = 0.95$; $RSD = 12.03$; $P < 0.001$) (3.1)

Saskatoon: $Y = 18.54 + 1.285 X$ ($R2 = 0.95$; $RSD = 12.19$; $P < 0.001$) (3.2)

The adjusted CERES data (Y_{adj}) were then compared with the recorded data (Fig. 3.1) as follows : Melfort : $Y_{adj} = 0.0017 + 1.0002X$ (3.3)

Saskatoon : $Y_{adj} = -0.0086 + 1.0002X$ (3.4)

For both equations 3.3 and 3.4 the intercept was not significantly different from zero and the slope was not significantly different from unity indicating close agreement between the adjusted CERES data and the recorded data. Equations 3.1 and 3.2 where then applied to the CERES data generated within GrassGro for the years 2010-2099 for Melfort and Saskatoon respectively. The resulting adjusted values were then used as input data for daily pan evaporation for 2010-2099 after adjustment from monthly to daily data by dividing each monthly total by the number of days in the month, with appropriate allowances for February in leap years.

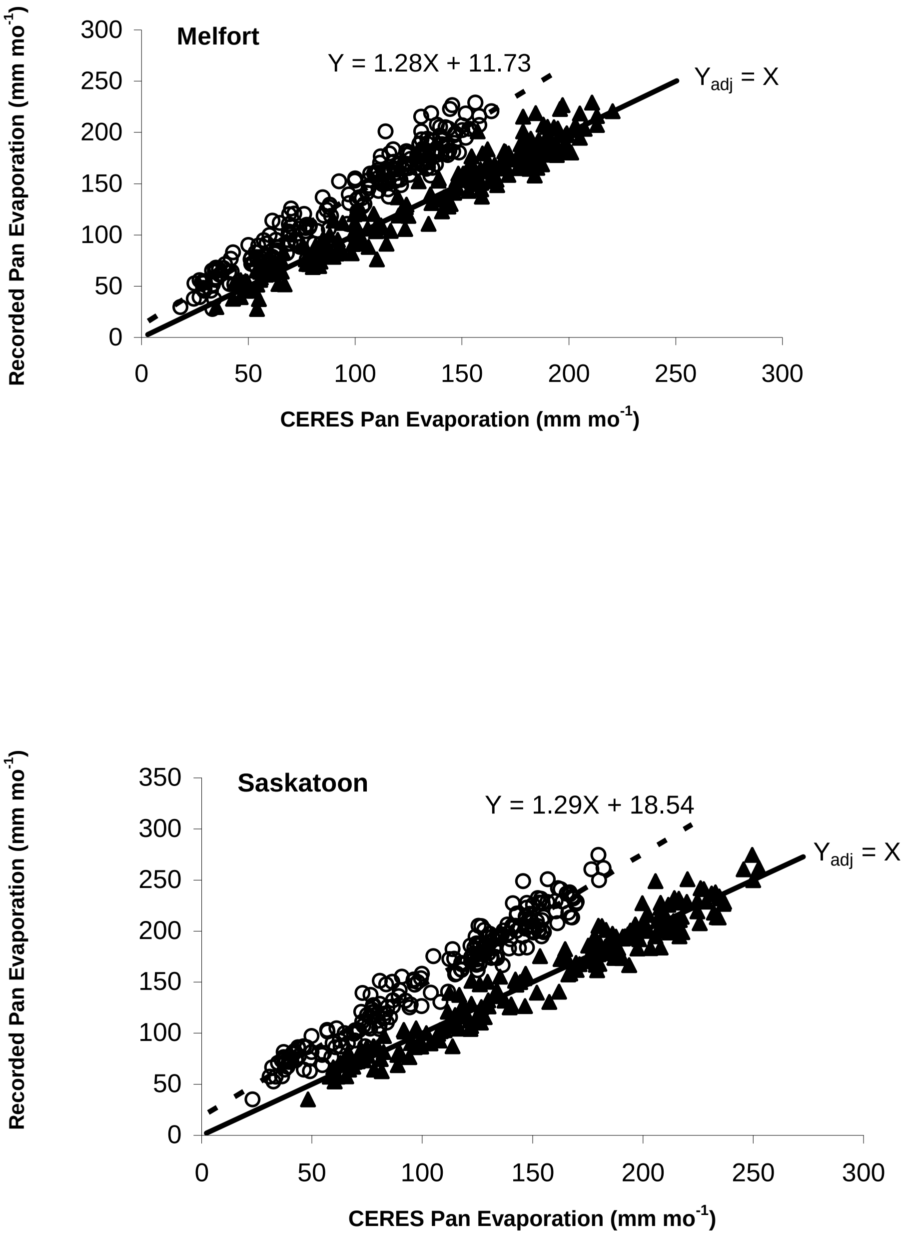


Figure 3.1 Regression of recorded mean pan evaporation (mm mo^{-1}) on CERES predicted (open circle, broken line) and CERES adjusted (closed triangle, solid line) mean pan evaporation (mm mo^{-1}) at Melfort and Saskatoon, Saskatchewan 1961-1990 R^2=0.95; P<0.001).

3.3.2 Comparisons between Baseline Data (1961-1990) and Projected Data (2040-2069)

3.3.2.1 Evaporation

Total evaporation (TE) simulated by GrassGro is the sum of evaporation by transpiration, surface and soil evaporation. Although GrassGro provides data for predicted TE during winter, these predictions are not included here because winter is the season of pasture dormancy with relatively small daily fluctuations in TE. Mean monthly TE increased ($P < 0.05$) from baseline values for the 30-yr time period of 2040-2069 with the CGCM2 A21 and CSIROMk2 B11 scenarios at Melfort and with the CSIROMk2 B11 scenario at Saskatoon for the spring (March-May) season (Figure 3.2). This increase coincides with the increased Min T and Max T during the 2040-2069 time period (Table 3.3). Mean monthly TE increased ($P<0.05$) from baseline values with the CSIROMk2 B11 and HADCM3 A21 scenarios during the summer (June-August) and fall (September- November) seasons at both locations. CGCM2 A21 predicted a similar trend at Melfort but a decrease at Saskatoon, though this was significant ($P<0.05$) only in the fall. The significant decrease in predicted mean monthly TE during the fall at Saskatoon was attributed to a decrease in soil evaporation and PET-AET.

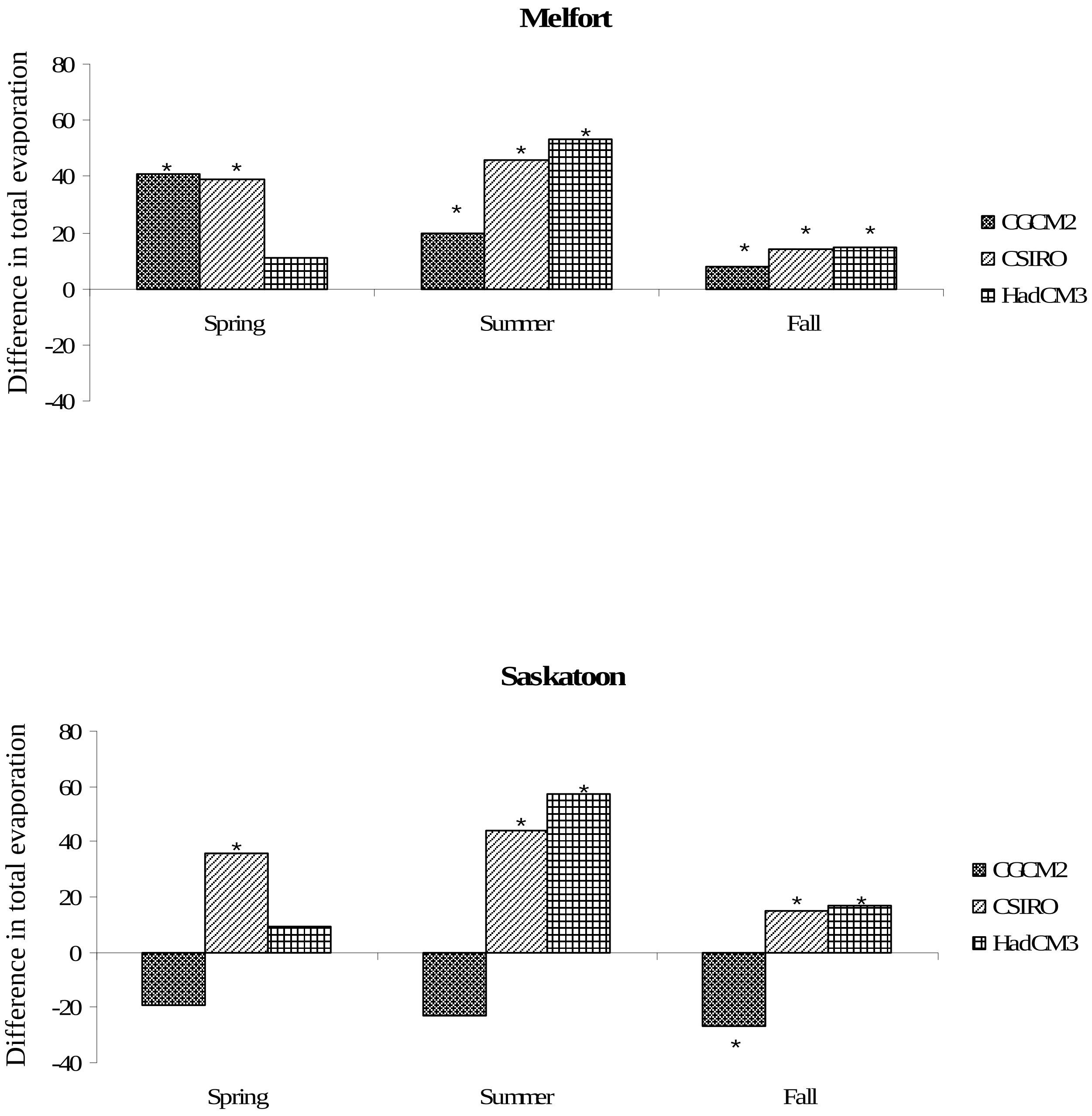


Figure 3.2 Difference in simulated total evaporation (mm) (transpiration, soil evaporation, surface evaporation, and PET-AET) for a baseline time period (1961-1990) and a future time period (2040-2069) projected by three climate change models (CGCM2 A21, CSIROMk2 B11 and HadCM3 A21). Significant differences ($P<0.05$) between baseline and projected data are indicated by *.

Table 3.3 Mean seasonal climate data at Melfort and Saskatoon recorded 1961-1990 (baseline) and projected for 2040-2069 from three climate change models (CGCM2 A21, CSIROMk2 B11 and HadCM3 A21). Values in parentheses indicate a change (+ or -) from baseline and * indicates differences from baseline were significant (P<0.05).

	Melfort				**Saskatoon**			
Element	**Baseline**	**CGCM2**	**CSIRO**	**HadCM3**	**Baseline**	**CGCM2**	**CSIRO**	**HadCM3**
Winter								
Precipitation (mm)	60	68 (13%)	88 (47%)	75 (25%)	52	48 (-8)	50 (4%)	62 (19%)
Maximum Temperature (°C)	-12.3	-9.2 (+3.1)*	-8.9 (+3.4)*	-11.5 (+0.8)	-10.2	-7.5 (+2.7)	-6.8 (+3.4)*	-9.4 (+0.8)
Minimum Temperature (°C)	-22.6	-18.0 (+4.6)*	-17.3 (+5.3)*	-21.8 (+0.8)	-20.3	-13.0 (+7.3)*	-15.4 (+4.9)*	-19.4 (+0.9)
Spring								
Precipitation (mm)	95	110 (+16%)	112 (+18%)	128* (+35%)	82	94 (+15%)	86 (+5%)	108* (+32%)
Maximum Temperature (°C)	7.6	14* (+6.4)	10* (+2.4)	8.4 (+0.8)	9	12.8* (+3.8)	12* (+3)	10 (+1)
Minimum Temperature (°C)	-4.9	2.7* (+7.6)	0.22* (+5.1)	-3.7* (+1.2)	-3.1	1.9* (+5.0)	0.65* (+3.8)	-1.9* (+1.2)
Evaporation (mm)	229	270* (+41)	268* (+39)	240 (+11)	276	257 (-19)	312* (+36)	285 (+9)
Summer								
Precipitation (mm)	194	181 (-7%)	172 (-13%)	172 (-13%)	156	161 (+3%)	161 (+3%)	167 (+7%)
Maximum Temperature (°C)	23	27* (+4)	27* (+4)	26* (+3)	24	27* (+3)	28* (+4)	27* (+3)
Minimum Temperature (°C)	9.8	13* (+3.2)	15* (+5.2)	15* (+5.2)	11	13* (+2)	14* (+3)	13* (+2)
Evaporation (mm)	414	434* (+20)	460* (+46)	467* (+53)	471	448 (-23)	515* (+44)	528* (+57)
Fall								
Precipitation (mm)	92	80 (-15%)	93 (+1%)	86 (-7%)	63	62 (-2%)	65 (+3%)	63 (0)
Maximum Temperature (°C)	7.6	10* (+2.4)	11* (+3.4)	10* (+2.4)	9	10.9* (+1.9)	12* (+3)	12* (+3)
Minimum Temperature (°C)	-2.9	-1.8 * (+1.1)	1.4* (+4.3)	-0.36* (+2.5)	-2.1	-0.1 (+2.0)	1.1 (+3.2)*	0.34 (+2.4)*
Evaporation (mm)	126	134* (+8)	140* (+14)	141* (+15)	159	132* (-27)	174* (+15)	176* (+17)

3.3.2.2 Mean maximum and minimum temperature, precipitation and soil moisture

Mean recorded and projected seasonal climate data for Melfort and Saskatoon are presented in Table 3.3 and soil moisture data are presented in Table 3.4.

3.3.2.2.1 Winter

3.3.2.2.1.1 Melfort

Although the climate projections for Melfort predicted increases in mean winter precipitation of 47% (CSIROMk2 B11), 25% (HadCM3 A21) and 13% (CGCM2 A21) these predictions were not significantly different from the baseline data. Mean maximum temperature (Max T) projections increased 3.1 and 3.4 ^{o}C with CGCM2 A21 and CSIROMk2 B11 respectively ($P<0.05$) but the HadCM3 projected increase of 0.8 ^{o}C did not differ from baseline data. Mean minimum temperature (Min T) projections increased ($P<0.05$) 5.3 ^{o}C (CSIROMk2 B11) and 4.6 ^{o}C (CGCM2 A21) but the HadCM3 A21 projected increase (0.8 ^{o}C) did not differ from baseline data.

3.3.2.2.1.2 Saskatoon

Climate projections for Saskatoon predicted changes in precipitation of -8% (CGCM2 A21), +19% (HadCM3 A21) and +4% (CSIROMk2 B11) but these predictions were not significantly different from the baseline data. Mean Max T projections increased 3.4 and 2.7 ^{o}C CSIROMk2 B11 and CGCM2 A21 relative to baseline data respectively ($P<0.05$) but the HadCM3 A21 projected increase of 0.8 ^{o}C did not differ from baseline data ($P>0.05$). Mean Min T projections increased significantly ($P<0.05$) by 4.9 and 7.3 ^{o}C for CSIROMk2 B11 and CGCM2 A21, respectively, but the HadCM3 A21 projected increase of 0.9 ^{o}C did not differ from baseline data.

Soil moisture data for winter are not presented because this is the season of pasture dormancy.

3.3.2.2.2 Spring

3.3.2.2.2.1 Melfort

HadCM3 A21 projected an increase in spring precipitation from the baseline of 35% ($P<0.05$), an insignificant change in mean Max T of 0.8 °C and a significant increase of 1.2 °C ($P<0.05$) in mean Min T (Table 3.3). The mean total soil moisture was calculated by taking the predicted mean of the whole soil profile (top soil + sub soil) to a depth of 1220 mm. The increase in spring precipitation (Table 3.3) was reflected in the predicted mean total soil moisture that increased 1.1% from the baseline value ($P<0.05$) for the SL/SCL association and 1.4% ($P<0.05$) for the L/L association (Table 3.4). When individual layers through the soil profile were considered (Table 3.4), there was no significant change in the 0-140 mm layer for L/L and a decrease for SL/SCL suggesting that surface evaporation was higher for the SL/SCL soil texture. At the 430-580 mm soil layer for both soil textures, there was an increase from baseline values however, this was only significant for the L/L soil texture ($P<0.05$). This indicates greater moisture retention in the L than the SCL subsoil. CSIROMk2 B11 projected an increase in precipitation of 18% above baseline (Table 3.3) but the increase was not significant. Mean Max T and Min T both increased (2.4 and 5.1 °C respectively; $P<0.05$). Even with the significant rise in both mean Max T and Min T, total soil moisture (0 to 1220 mm) increased for both soil texture profiles, 20.5% for SL/SCL ($P<0.05$) and 21.3% for L/L ($P<0.05$). An interesting finding for the CSIROMk2 B11 was a decrease in moisture in the 0-140 mm soil layer of 0.9 and 1.4% for the SL/SCL and L/L textured soils respectively corresponding with the increase in evaporation projected by this climate scenario. However, simulation of soil moisture at the 430-580 mm layer of the L/L soil indicated an increase in soil moisture, suggesting the ability of the loam texture to retain moisture at depth. This could be a potential benefit to plant species with deep rooting ability.

CGCM2 A21 projected the driest and warmest spring of the three climate scenarios at Melfort (Table 3.3). Although there was a 16% increase in precipitation from baseline, this was not significant. Mean Max T and Min T increases from baseline were greater for CGCM2 A21 than the other two climate change scenarios with projected increases of 6.4 and 7.6 ^{o}C, respectively, ($P<0.05$; Table 3. 3). Although the increase in mean Max T and Min T might be expected to decrease soil moisture from baseline values, total soil moisture did not differ significantly probably due to the projected increase in precipitation. Nevertheless, the upper soil layer did show a significant decrease in soil moisture from the baseline values of about 1% for SL/SCL and 1.4% for L/L ($P<0.05$) which coincides with an increase in evaporation. There was no significant change in soil moisture for the 430-580 mm soil layer for the L/L soil texture, however, the SL/SCL soil texture significantly decreased in relation to the baseline ($P<0.05$).

3.3.2.2.2.2 Saskatoon

HadCM3 A21 projected the greatest increase in precipitation of the three climate scenarios at Saskatoon in spring with an increase of 32% from the baseline ($P<0.05$), no significant change in mean Max T, and an increase of 1.2 ^{o}C ($P<0.05$) in mean Min T (Table 3.3). The increase in precipitation was reflected in the total mean soil moisture which increased from the baseline value of 17.1 to 18.6% ($P<0.05$) for the SL/SCL association (Table 3.4). Mean total soil moisture responded similarly for the L/L textured soil with an increase from 15.2 to 17.2% ($P<0.05$; Table 3.4). When individual layers were considered, significant increases ($P<0.05$) from baseline values were projected for both the 0-140 and 430-580 mm soil layers (Table 3.4). The 0-140 mm soil layer increased by 0.6% (SL/SCL) and 0.9% (L/L) and by 1.8% (SL/SCL) and 1.6% (L/L) for the 430-580 mm soil layer suggesting moisture penetrated to all layers of the soil profile.

CSIROMk2 B11 projected no significant change in precipitation from the baseline. Mean Max T and Min T both increased by (3.0 and 3.8^{o}C, respectively; $P<0.05$). Even with the significant rise in both mean Max T and Min T, total soil moisture did not change significantly from baseline values. However, CSIROMk2 B11 did predict a decrease in soil moisture at the 0-140 mm soil layer of 0.8% for the SL/SCL ($P<0.05$) corresponding with the significant increase (36 mm) in evaporation projected by this climate scenario (Table 3.3). There was no projected change from baseline for the L/L textured soil for the 0-140 mm soil layer, corresponding to the lack of projected increases in evaporation. No significant change in soil moisture from baseline values was detected at the 430-580 mm layer for both soil textures.

The CGCM2 A21 scenario projected an increase in precipitation of 15% ($P<0.05$) from the baseline value (Table 3.3). Mean Max T and Min T both increased ($P<0.05$) by 3.8 and 5.0 ^{o}C, respectively. These were the greatest projected increases from the baseline values of the three climate scenarios. Even with the significant increases in temperature, the CGCM2 A21 projected an increase ($P<0.05$) in mean total soil moisture from baseline values of 17.1 to 18.8% for the SL/SCL association (Table 3.4). Mean total soil moisture responded similarly for the L/L textured soil with an increase of 2.5% ($P<0.05$; Table 3.4). When individual layers were considered, significant increases were projected for both the 0-140 mm and 430-580 mm soil layer from baseline values. The 0-140 mm soil layer increased by 0.7% (SL/SCL) and 1% (L/L) and by 2.1% (SL/SCL) and 2.6% (L/L) for the 430-580 mm soil layer. All were significantly different from the baseline values ($P<0.05$; Table 3.4) suggesting moisture penetrated to all layers of the soil profile.

3.3.2.2.3 Summer

3.3.2.2.3.1 Melfort

Both the HadCM3 A21 and CSIROMk2 B11 scenarios projected a decrease of 13% relative to baseline precipitation during summer at Melfort but the difference was not significant. Mean Min T was projected to increase by 5.2^{o}C for both climate scenarios ($P<0.05$) and mean Max T increased by 3^{o}C for HadCM3 A21 and 4^{o}C for CSIROMk2 B11 ($P<0.05$). Projected mean total soil moisture for CGCM2 A21 for SL/SCL and CSIROMk2 B11 for L/ L did not change from baseline values.

HadCM3 A21, projected a significant increase in mean total soil moisture for the L/L soil texture ($P<0.05$). Significant decreases in soil moisture were projected by HadCM3 A21 for both soil textures 0.7% (SL/SCL) and 0.9% (L/L) and by 1.1% for

CSIROMk2 B11 for the L/L soil texture for the 0-140 mm soil layer ($P<0.05$). There was no significant change in soil moisture at the 430-580 mm soil layer for both soil textures. The decrease in soil moisture at the 0-140 mm layer probably reflects the decrease in precipitation in conjunction with the increase in mean Max T and Min T. What differentiates the significant decrease of 1.1% projected by the CSIROMk2 B11 climate change scenario is the greater projected increase in evaporation of 53 mm in comparison to 43mm for HadCM3 A21 (Table 3.3).

CGCM2 A21 projected no significant change in precipitation. Mean Max T and Min T both increased (4 and 3.2^{o}C, respectively) from baseline values ($P<0.05$). No significant change-to total mean soil moisture and soil moisture at both soil layers (0-140 and 430-580 mm) was projected with the CGCM2 A21 for the SL/SCL soil texture however there was a significant increase in total mean soil moisture by 0.6% for the L/L texture soil. This suggests the L/L texture can retain more moisture than the SL/SCL.

Table 3.4 Mean (±SD) simulated seasonal and annual soil moisture (%) through the total profile (0-1220 mm), 0-140 mm and 430-580 mm for 1961-1990 (baseline) and 2040-2069 projected from three climate change models (CGCM2 A21, CSIROMk2 B11 and HadCM3 A21) at Melfort and Saskatoon, Saskatchewan for soils of sandy loam/sandy clay loam (SL/SCL) and loam/loam (L/L) texture.

			Melfort				Saskatoon			
Texture/depth	Period	Source	Spring	Summer	Fall	Annual	Spring	Summer	Fall	Annual
SL/SCL 0-1220 mm	1961-1990	Baseline	19.8±1.8	17.3±1.0	17.5±1.1	18.2±0.7	17.1±1.4	16.5±0.7	16.3±0.9	16.6±0.7
	2040-2069	CGCM2	19.4±2.1	17.6±1.8	17.4±0.9	18.1±1.0	18.8±2.0*	17.5±1.7*	17.0±0.9*	17.8±1.0*
		CSIRO	20.5±1.9	17.4±1.5	17.9±1.6	18.6±1.0	17.3±1.4	16.9±0.6*	16.8±0.9*	17.0±0.7*
		HadCM3	20.9±2.2	17.4±1.1	17.5±1.7	18.6±1.1	18.6±1.8*	17.1±0.9*	16.7±0.8*	17.5±0.8*
L/L 0-1220 mm	1961-1990	Baseline	20.3±1.8	18.0±1.1	18.3±1.1	18.9±0.8	15.2±1.4	14.7±0.7	14.5±0.8	14.8±0.7
	2040-2069	CGCM2	20.3±2.0	18.6±1.7*	18.4±0.9	19.1±1.0	17.7±2.4*	16.4±2.0*	16.1±0.9*	16.8±1.2*
		CSIRO	21.3±1.9*	18.5±1.4	18.9±1.6	19.6±1.0*	14.9±1.4	14.6±0.6	14.5±0.8	14.7±0.7
		HadCM3	21.7±2.2*	18.5±1.1*	18.5±1.7	19.6±1.1*	17.2±1.8*	16.0±1.1*	15.6±0.7*	16.3±0.9*
SL/SCL 0-140 mm	1961-1990	Baseline	16.1±1.4	13.6±1.3	15.2±2.0	15.0±0.7	13.9±1.4	12.6±0.9	12.8±1.5	13.1±0.7
	2040-2069	CGCM2	15.1±1.4*	13.5±1.9	14.4±2.1	14.4±0.9*	14.6±1.4*	13.4±1.8*	14.0±1.9*	14.0±0.8*
		CSIRO	15.2±1.3*	13.1±1.9	14.9±2.1	14.4±1.2*	13.1±1.2*	12.7±0.9	12.8±1.4	12.9±0.6*
		HadCM3	16.2±1.4	12.9±1.3*	14.3±2.0	14.5±0.9*	14.5±1.5*	12.3±0.8	12.4±1.3	13.0±0.8
L/L 0-140 mm	1961-1990	Baseline	20.0±1.9	16.2±1.7	18.3±2.8	18.2±1.0	16.7±2.0	15.0±1.3	15.2±2.0	15.6±1.0
	2040-2069	CGCM2	18.6±1.9*	16.1±2.5	17.2±2.6*	17.3±1.1*	17.7±2.0*	15.6±2.6*	16.7±2.4*	16.8±1.1*
		CSIRO	18.6±1.6*	15.1±2.5	18.0±2.9	17.5±1.5*	15.7±1.8	15.0±1.3	15.1±1.9*	15.3±0.9*
		HadCM3	20.0±2.0	15.3±1.8*	17.0±2.8*	17.5±1.7*	17.6±2.1*	14.6±1.0	14.6±1.8*	15.6±1.1
SL/SCL 430-580 mm	1961-1990	Baseline	21.2±3.3	16.7±1.2	16.9±2.2	18.3±1.3	17.4±2.6	16.7±1.2	16.3±1.2	16.8±1.2
	2040-2069	CGCM2	20.1±3.6	17.2±2.2	17.0±1.8	18.1±1.6	19.5±3.5*	17.3±2.1	16.8±1.6	17.9±1.6*
		CSIRO	22.3±2.7	17.2±1.9	17.7±2.8	19.1±1.5*	17.4±2.6	17.0±1.5	16.7±1.7	17.0±1.3
		HadCM3	22.7±3.3	17.3±1.6	17.3±2.7	19.1±1.6*	19.2±3.6*	17.0±1.6	16.3±1.3	17.5±1.5*
L/L 430-580 mm	1961-1990	Baseline	18.2±4.8	14.2±1.7	13.7±1.8	15.4±1.9	14.2±2.9	13.6±1.5	13.5±1.7	13.0±1.5
	2040-2069	CGCM2	17.8±4.7	14.7±2.8	13.8±1.6	15.4±2.2	16.8±4.5*	14.8±3.1	13.8±1.9	15.1±2.5*
		CSIRO	20.0±4.7	14.7±2.2	14.5±2.8	16.4±2.0*	14.2±2.8	13.6±1.0	13.5±1.6	13.7±1.4
		HadCM3	20.2±4.9*	14.9±1.8	14.4±2.8	16.5±2.0*	15.8±4.0*	14.3±1.9*	13.6±1.9	14.6±1.9*

3.3.2.2.3.2 Saskatoon

HadCM3 A21 projected a non-significant increase in precipitation from the baseline of 7% while mean Max T and Min T increased (3 and 2^{o}C respectively; $P<0.05$; Table 3.3). Mean total soil moisture increased from the baseline of 16.5 to 17.1% for the SL/SCL soil texture ($P<0.05$). Mean total soil moisture also increased 1.3% for the L/L soil texture ($P<0.05$). No significant change was projected to soil moisture for the 0-140 mm layer for both soil textures (Table 3.4). Soil moisture for both soil textures increased from the baseline by 0.7% for the SL/SCL texture and 1.3% for the L/L textured soil for the 430-580 mm layer ($P<0.05$; Table 3.4).

CSIROMk2 B11 projected an increase in precipitation from the baseline of 3%, although this was not significant. Mean Max T and Min T increased by 4 and 3^{o}C, respectively ($P<0.05$). Mean total soil moisture increased from baseline of 16.5 to 16.9% ($P<0.05$) for the SL/SCL texture but there was no change for the L/L texture soil. When individual soil layers were considered, there were no significant changes from baseline values for both soil textures and both soil layers.

CGCM2 A21 projected an increase in precipitation from the baseline of 3% although again, this was not significant. Mean Max T and Min T both increased (3 and 2^{o}C respectively; $P<0.05$; Table 3.3). Mean total soil moisture increased from the baseline by 1.0% (SL/ SCL) and 1.7% (L/L) reflecting the slight increase in projected precipitation but the changes were not significant (Table 3.4). Soil moisture increased ($P<0.05$) from baseline values for the 0-140 mm layer for both soil textures (0.8% SL/SCL and 0.6% L/L) but in the 430-580 mm soil layer there was a projected increase in soil moisture of 1.2% ($P<0.05$) for L/L, suggesting that the moisture was able to penetrate throughout the total profile (Table 3.4).

3.3.2.2.4 Fall

3.3.2.2.4.1 Melfort

The fall season at Melfort provided a wide variation in projected climate from all three climate change scenarios. All climate change scenarios projected non-significant changes in precipitation although the projections ranged from decreases of 15% (CGCM2 A21) and 7% (HadCM3 A21) to a slight increase of 1% (CSIROMk2 B11) relative to baseline data.

Mean Max T was projected to increase by 2.4 ^{o}C ($P<0.05$) for both the CGCM2 A21 and HadCM3 A21 relative to baseline. The mean Min T was projected to increase by 1.1 and 2.5^{o}C (CGCM2 A21 and HadCM3 A21, respectively) ($P<0.05$). Simulated total mean soil moisture was unchanged with both HadCM3 and CGCM2 A21. CSIROMk2 B11 projected the greatest increase in mean Max T and Min T (3.4 and 4.3^{o}C, respectively; $P<0.05$). The small and non-significant increase of 1% in precipitation projected by CSIROMk2 B11 resulted in a small and non-significant increase in simulated mean total soil moisture relative to the baseline for both soil textures.

When the individual layers were considered, all climate change scenarios projected no change in moisture from the baseline values for both soil texture at the 430-580 mm layer but at the 0-140 mm layer there was a decrease ($P<0.05$) in soil moisture projected by CGCM2 A21 from 18.3 to 17.2% and HadCM3 A21 from 18.3 to 17.0% for the L/L texture. For the SL/ SCL soil texture, all three climate scenarios projected a non-significant decrease in soil moisture at the 0-140 mm layer.

3.3.2.2.4.2 Saskatoon

HadCM3 A21 projected no change in precipitation but mean Max T and Min T increased by 3 ^{o}C and 2.4 ^{o}C respectively ($P<0.05$). Mean total soil moisture increased from 16.3 to 16.7% ($P<0.05$) for the SL/ SCL and from 14.5 to 15.6% ($P<0.05$) for the L/L textured soils (Table 3.4). However, there was no significant change in soil moisture at either 0-140 or 430-580 mm for the SL/SCL soil texture ($P>0.05$) indicating that these increases in total soil moisture occurred at depths greater than 580 mm. For the L/L soil texture there was a decrease in soil moisture at 0-140 mm from 15.2 to 14.6% ($P<0.05$) but no change at the 430-580 mm layer.

CSIROMk2 B11 projected an increase in precipitation of 3% above baseline but this was not significant. Mean Max T and Min T both increased (3 and 3.2 ^{o}C respectively; $P<0.05$). Mean total soil moisture increased from 16.3 to 16.8% ($P<0.05$) for the (SL/ SCL) texture, but no change in moisture was simulated for the L/L texture.

CGCM2 A21 projected a non-significant decrease in precipitation of 2% and mean Max T and Min T both increased (1.9 and 2 ^{o}C respectively; $P<0.05$). Mean total soil moisture significantly increased from 16.3 to 17% for SL/SCL and 14.5 to 16.1% ($P<0.05$) for the L/L textured soils. The increase in mean total soil moisture can be attributed to the decrease in soil evaporation with this climate change scenario. There were siginificat increases ($P<0.05$) in soil moisture at 0-140 mm from 12.8 to 14.0%

SL/SCL and 15.2 to 16.7% L/L texture. This was the only climate change scenario to project an increase in surface soil moisture.

3.4 Conclusion

The Canadian (CGCM2 A21) climate scenario projected greater climate warming than either CSIROMk2 B11 or HadCM3 A21 at all locations during 2040-2069. This was especially apperent during the spring with increases in Max T 6.4 and 3.8 ^{o}C and Min T 7.6 and 5.0 ^{o}C by Melfort and Saskatoon respectively. The differences between models were most prominent during the winter and spring. These results agree with previous regional projections of temperature using the same climate change scenarios (e.g., Wheaton, 2001; Barrow, 2001; Clark et al., 2000).

At all locations in this study the greatest projected increase in precipitation occurred during spring. HadCM3 projected increases in precipitation as high as 35% at Melfort. These findings are similar to previous simulated data on a provincial scale (Wheaton, 2001). Of the climate models used in GrassGro to predict soil moisture, only HadCM3 predicted an increase in mean total soil moisture in both soil textures at both locations during spring ($P<0.05$). CGCM2 A21 predicted increased mean total soil moisture during all seasons at Saskatoon ($P<0.05$) but no changes at Melfort except during summer on the L/L soil. The increases with the CGCM2 A21 scenario should be evaluated with caution as the model uses poor land surface parameterizations and uses the standard bucket hydrology scheme. The confidence in the simulations by the CGCM2 A21 scenario may not be high.

CSIROMk2 B11 predicted increased soil moisture during summer and fall for the SL/SCL at Saskatoon and for Melfort during spring but only on the L/L soil ($P<0.05$).

The results from the two soil textures indicate that soils of even small differences in texture will respond differently to climatic variables with respect to moisture content. In coarse textured soils, rain water drains quickly to lower soil layers where it is protected from direct soil evaporation, where as fine textured soils moisture is held near the surface. Therefore soil texture will be an important variable to evaluate when developing adaptation strategies.

Soil moisture is so closely associated with climate (precipitation, temperature, solar radiation, wind), plant cover, plant growth and soil texture that these factors cannot be used in isolation but must be integrated into a single decision support tool with a daily time step such as GrassGro to be of real value in predicting the effects of climate change on agricultural production. A daily time step will be important when determining adaptation strategies at the farm level since soil moisture and biological changes in agriculture occur in relation to climate on a daily rather than a monthly or yearly time step. The effects of climate change on the production of two forage grasses will be reported in Chapter 4.

CHAPTER 4

4.0 SIMULATION OF THE PRODUCTION AND QUALITY OF CRESTED WHEATGRASS (*Agropyron cristatum*) AND HYBRID BROMEGRASS (*Bromus riparius* X *Bromus inermis*) AT TWO LOCATIONS IN SASKATCHEWAN, CANADA USING THREE GLOBAL CLIMATE CHANGE SCENARIOS.

4.1 Introduction

The ability of a DST such as GrassGro to determine future changes to forage production resulting from anthropogenic climate change has improved in the last 10 years because climate models now include more understanding of the complex cycling, of atmospheric gases and ocean patterns, causing variation in climate (IPCC, 2007).

There are concerns among agriculturalists that anthropogenic causes of climate change may result in detrimental changes to forage quality and production. Previous studies used an overall increase of temperature by 2°C and a doubling of the atmospheric gas carbon dioxide to determine responses of plant growth (Morison and Morecroft, 2006), morphology and animal productivity (Rotter and van Geijn, 1999). Plant response will differ depending on site-specific soil characteristics such as texture and depth and also depending on the species of plants. Previous studies have evaluated general responses to non-specific C3 and C4 plants to climate change (Coffin and Lauenroth, 1996) and on cropping species (Tubiello et al., 2000). However there have been few evaluations at site-specific locations using specific forage species.

Decision support tools (DST) that integrate multiple factors are now available to determine the response of different plant species to specific global climate scenarios affecting regional climatic variables such as daily minimum and maximum temperature, wind, evaporation, solar radiation and precipitation. GrassGro (Moore et al., 1997) is one such DST that can be used to evaluate the responses of different plant species to climatic changes at site-specific locations.

The identification of forage species that can maintain or improve production during various future climate change scenarios will be valuable to pastoralists. Literature concerning the response of different forage species to future climate change scenarios is lacking for the Canadian Prairies. Crested wheat grass (*Agropyron cristatum*) can withstand severe droughts (Coulman et al., 1999). During the 1930s and 1960s many of the native pastures species were tilled and reseeded with introduced species such as crested wheatgrass (Rogler and Lorenz, 1983; DuPuit, 1986). In Saskatchewan and Alberta alone this species is seeded to 1.5 million ha (Henderson, 2005). Hybrid brome grass (*Bromus riparius* x *Bromus inermis*) is a cross between smooth brome grass and meadow brome grass (Knowles and Baron, 1990). This species is relatively new, only becoming commercially available in 2002 and not yet well documented in the literature (Ferdinandez and Coulman, 2001). Smooth bromegrass is well known for its drought tolerance (Vogel et al., 1996), however, the vulnerability of hybrid brome to various future climatic scenarios is unknown. Although tame species have been tested for resilience to stress disturbances, future climatic situations may be beyond the range of the species to cope.

In Chapter 3, it was reported that climate change projected for 2040-2069 from three global climate models (GCMs) would result in significant changes to temperature, precipitation and available soil moisture at Melfort and Saskatoon, Saskatchewan. The present chapter discusses the simulated effects of climate change on the production and quality of monospecific pastures of crested wheatgrass and hybrid bromegrass on soils of two textures at two locations in Saskatchewan, Canada.

4.2 Methodology

4.2.1 Decision Support Tool, Locations and Climate Scenarios

The Canadian version of GrassGro (Cohen et al., 2003; Cohen et al., 2004a; Perillat et al., 2004; Lynch et al., 2005) was the Decision Support Tool (DST) used for all simulations. Two locations in Saskatchewan were chosen for simulations of forage production and quality: (Melfort 52 º 49’N 104 º 36’ W, elevation 480 m and Saskatoon 52 º 10’N 106 º 41’ W, elevation 501 m) and three global climate models were used in the simulations. These were: the Canadian Climate Centre Model (CGCM2 A21) of the second generation (3.75° x 3.75° resolution grid about 400 km) (Flato and Boer, 2001); Hadley Climate Model (HadCM3 A21) of the third generation (2.5° x 3.75°) (Gordon et al., 2000; Pope et al., 2000); Commonwealth Scientific and Industrial Research Organization (CSIROMk2 B11; 5.6° x 3.2°) (Hirst et al., 1996; Hirst et al., 2000). Detailed descriptions of the GrassGro DST and climate change change scenarios have been given in Chapters 2 and 3 and the methodology used to apply daily data to the future time periods has been described in Chapter 3. This chapter compares simulated pasture production and quality data for 1961-1990 with that for 2040-2069.

4.2.2 Pastures and Soils

Two mono-specific pastures were included in the simulations. These were crested wheatgrass (*Agropyron cristatum*) and hybrid bromegrass (*Bromus riparius* x *Bromus inermis*). The grasses were parameterized for GrassGro by Cohen et al. (1995; crested wheatgrass), and Thompson (2003; hybrid bromegrass). Two soil texture associations were assumed at each location. These were: Loam topsoil / Loam subsoil (L/L) and Sandy-loam topsoil / Sandy-clay-loam subsoil (SL/SCL). In each soil association, the topsoil depth was assumed to be 280 mm and subsoil depth was assumed to be 1220 mm. A programmed removal of the standing crop every year on November 30 was included to allow effective use of light for new growth which would be impeded by the large build up of dead herbage and litter if it was not removed .

4.2.3 GrassGro Simulations

Simulations used observed climate datasets from both locations for the time period 1961-1990 (baseline) and climate data generated from three climate scenarios for the 2050s time period (2040-2069) as described in Chapter 3 to predict mean availability, protein content and digestibility of green and total herbage dry matter (DM) and the factors limiting growth. A limitation to this study was the ability of GrassGro to account for any possible direct plant production response to elevated levels of CO_2.

4.2.4 Statistical Analysis

Differences between simulated production and quality data using baseline climate data (1961-1990) and climate data projected by the three climate change models for 2040-2069 were assessed by T-test at the 5% significance level using Statistix 7 (Analytical Software, 2000).

4.3 Results and Discussion

4.3.1 Mean Available Herbage

Simulated data for mean available herbage of crested wheatgrass and hybrid bromegrass are presented in Tables 4.1 and 4.2, respectively.

4.3.1.1 Crested Wheatgrass

4.3.1.1.1 Spring

On the SL/SCL soil at Melfort during spring, simulations using the CGCM2 A21 and CSIROMk2 B11 scenarios indicated significant increases ($P<0.05$) from baseline during 2040-2069 for mean green available herbage (MGAH) of 303 and 172 kg ha^{-1}, respectively, but no significant change in mean total available herbage (MTAH; Table 4.1). These results reflect the significant increases in both maximum and minimum temperatures reported previously in Chapter 3, however, precipitation was not significantly greater. In contrast, HadCM3 A21 projected non-significant ($P>0.05$) decreases of 44 and 263 kg ha^{-1} for MGAH and MTAH respectively despite the significant increase in spring precipitation (Chapter 3). These results are reflected in Figure 4.1a which indicates that the effects of temperature and light interception by new spring growth were more restrictive for baseline climate than for CGCM2 A21 and CSIROMk2 B11 but relatively similar for HadCM3 A21. GrassGro determines growth limiting factors by using a mixture of a multiplicative and a limiting factor approach to modeling the interacting factors of light, temperature and soil moisture availability based on an argument of Paltridge (1970). The term ‘light interception’ refers to the amount of green herbage that is available and its ability to intercept light for photosynthesis in the presence of dead herbage and, in the case of a multi-specific pasture, other species present in the sward. The larger increases in MGAH compared with MTAH (Table 4.1) reflect a component of decay of the standing dead and litter fractions of the sward following an increase in temperature. GrassGro uses data for daily temperature, soil moisture and solar radiation to predict the growth of green herbage, its contribution to the green herbage pool (MGAH) and also for the movement of green herbage into and out of the dead and litter pools by way of senescence and decay, respectively. The movement of herbage through these pools is affected differently by the various climatic variables such that the dynamics differ between the pools. Thus increases and decreases in MGAH are not necessarily reflected by similar changes in the MTAH.

On the SL/SCL soil at Saskatoon, CGCM2 A21 was the only climate scenario to project a significant increase ($P<0.05$) from baseline simulations in MGAH (401 kg ha^{-1}) for the 2040-2069 time period. MTAH increased by 722 kg ha^{-1} ($P<0.05$) with the CGCM2 A21 scenario for the 2040-2069 time period relative to the baseline, reflecting the increase in projected Max T and Min T by this scenario (Chapter 3) which reduced temperature as a growth limitation in comparison to the baseline (1961-1990) (Figure 4.1b). MTAH decreased from the baseline by 100 kg ha^{-1} with the CSIROMk2 B11 simulation ($P<0.05$). This decrease in MTAH was attributed to a reduction in water availability to the plant as reflected in the greater water limitation with the CSIROMk2 B11 scenario than the baseline (Figure 4.1b). The water limitation with this scenario was attributed to a lack of change in precipitation and an increase in evaporation resulting from the increase in Max T and Min T as discussed in Chapter 3.

The results of simulations for the L/L soil texture at Melfort were similar to the SL/SCL soil texture for both MGAH and MTAH except that the HadCM3 scenario predicted a significant reduction in MTAH of 175 kg ha^{-1} ($P<0.05$). All MGAH and MTAH values were slightly lower for the L/L soil texture suggesting a greater negative impact of climate change on the L/L soil when compared with the SL/SCL soil texture.

The results of simulations for the L/L soil texture at Saskatoon were very different from the SL/SCL soil texture for the MGAH. Significant increases ($P<0.05$) in MGAH were projected by CGCM2 A21 and HadCM2 A21 on the L/L soil texture but only with the CGCM2 A21 scenario for the SL/SCL soil texture. CSIROMk2 B11 scenario projected a significant decrease in MGAH on the L/L soil texture ($P<0.05$) while a small but non-significant increase from the baseline was projected on the SL/SCL.

4.3.1.1.2 Summer

All three future climate change scenario simulations for the SL/SCL soil texture at Melfort during summer 2040-2069 indicated decreases ($P<0.05$) in MGAH of 713, 591 and 575 kg ha^{-1} from the 1884 kg ha^{-1} baseline for CGCM2 A21, CSIROMk2 B11 and HadCM3 A21, respectively. The reduction in MGAH can be attributed to the combined limiting effects of temperature, water and light interception (the latter reflecting a smaller amount of green material) on growth relative to the baseline time period (Figure 4.1a). MTAH also decreased in the 2040-2069 time period by 226 kg ha^{-1} (CSIROMk2 B11), 435 kg ha^{-1} (CGCM2 A21) and 556 kg ha^{-1} (HadCM3 A21) from the baseline of 3906 kg ha^{-1}; however, only the change with the HadCM3 A21 scenario was significant ($P<0.05$). The significant decrease in MGAH during the summer season by the HadCM3 A21 climate scenario is attributed to the projected decrease in precipitation as well as the increase in both Max T and Min T and the consequent increase in evaporation (Chapter 3).

On the SL/SCL soil at Saskatoon, only the CGCM2 A21 scenario projected a significant increase (554 kg ha^{-1}) in MGAH from baseline simulations for the 2040-2069 time period ($P<0.05$). MTAH increased by 1755 kg ha^{-1} from the baseline ($P<0.05$) with the CGCM2 A21 scenario during summer 2040-2069. The CGCM2 A21 scenario indicated water and light was not as limiting during summer 2040-2069 relative to baseline (Figure 4.1b). This was attributed to the reduced evaporation projected with this scenario (Chapter 3). The CSIROMk2 B11 projected the only significant decrease in both MGAH (154 kg ha^{-1}) and MTAH (177 kg ha^{-1}) ($P<0.05$). The decrease in MGAH was the result of low light interception due to the low availability of green herbage and the greater than optimal temperatures for growth of crested wheatgrass (Figure 4.1b) causing heat stress. As reported in Chapter 3, mean maximum temperature increased by +4^{o}C in comparison to the baseline mean maximum temperature during this time period.

Simulated results for MGAH on the L/L soil at Melfort indicated that all climate change scenarios projected significant decreases from baseline values ($P<0.05$). However, MTAH did not change significantly from baseline values suggesting an increased rate of senescence and transfer from the green to the dead and litter pools. At Saskatoon, the results for MGAH and MTAH for the L/L soil were similar to the SL/SCL soil except that the decrease in MGAH relative to baseline predicted by CSIROMk2 B11 was not significant.

4.3.1.1.3 Fall

Simulated results for MGAH on the SL/SCL soil at Melfort during fall 2040-2069 were similar to those for summer. All three future climate scenarios predicted a decrease from the mean baseline value (1422 kg ha^{-1}) of 378, 410 and 556 kg ha^{-1} for CGCM2 A21, CSIROMk2 B11 and HadCM3 A21, respectively ($P<0.05$). MTAH also decreased from the baseline of 5027 kg ha^{-1} during this time period by 1170, 986 and 1104 kg ha^{-1} for CGCM2 A21, CSIROMk2 B11 and HadCM3 A21, respectively ($P<0.05$). Both the CGCM2 A21 and HadCM3 A21 scenarios projected decreases in precipitation (7% and 12%) while CSIROMk2 B11 projected a small increase (1%) and all scenarios projected a rise in mean maximum and minimum temperatures during fall 2040-2069 (Chapter 3). However, the poor availability of green herbage for light interception relative to baseline continued to be the major limitation to growth of crested wheatgras during fall at Melfort (Figure 4.1a) as a result of the reduced growth during summer, relative to baseline, due to the increased temperature and reduced precipitation (Chapter 3).

Similar to the predictions for summer on the SL/SCL soil at Saskatoon, the CGCM2 A21 scenario was the only climate scenario to project a significant increase from baseline simulations (400 kg ha^{-1}; $P<0.05$) in MGAH during fall 2040-2069. MTAH increased by 1866 kg ha^{-1} ($P<0.05$) from the baseline with the CGCM2 A21 scenario during fall 2040-2069. The CGCM2 A21 scenario projected that water and light interception were less limiting to growth during fall 2040-2069 than during the baseline period (1961-1990) (Figure 4.1b). This was probably due to the reduced evaporation projected by CGCM2 A21 (Table 3.3). CSIROMk2 B11 projected the only significant ($P<0.05$) decrease in both MGAH (61 kg ha^{-1}) and MTAH (353 kg ha^{-1}). The decrease in MGAH was probably the result of a reduced growth of green herbage during summer that carried on into fall (Figure 4.1b) due to the increased temperatures and evaporation projected by this scenario relative to baseline data (Chapter 3).

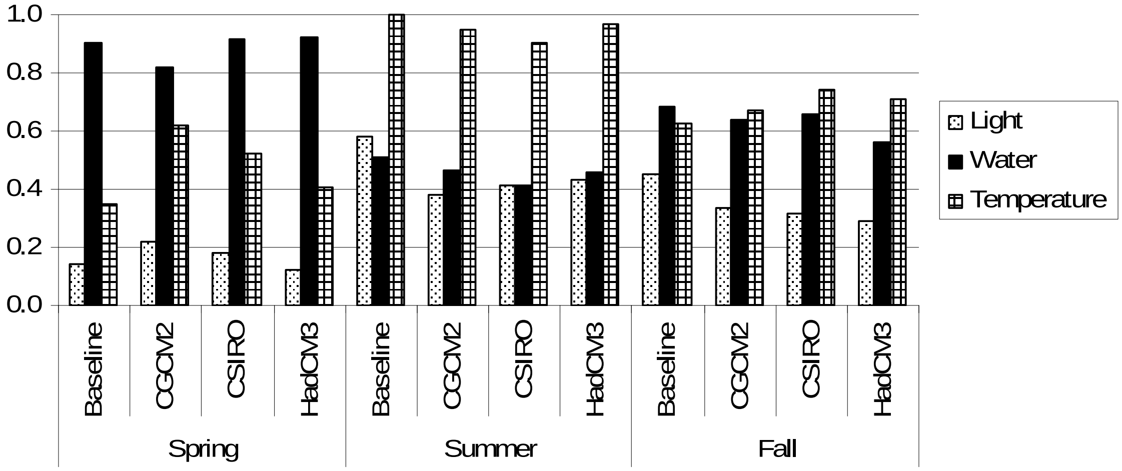
Simulations for the L/L soil at Melfort provided similar results to those for the SL/SCL soil for MGAH and MTAH with all climate scenarios projecting decreases from baseline values, however the decreases projected by CSIROMk2 B11 were not significant. At Saskatoon the results for the L/L soil were similar to the SL/SCL except that the increase relative to baseline projected by HadCM3 A21 was significant for MTAH ($P<0.05$).

4.3.1.2 Hybrid Bromegrass

4.3.1.2.1 Spring

The CGCM2 A21 and CSIROMk2 B11 scenarios simulated significant increases ($P<0.05$) from baseline simulations for MGAH of 645 and 352 kg ha^{-1}, respectively, and for MTAH of 443 and 248 kg ha^{-1}, respectively, (Table 4.2) on the SL/SCL soil at Melfort during spring. These results reflect the significant increases in both Max T and Min T, as well as, the non-significant increase in precipitation reported in Chapter 3. In contrast, HadCM3 projected a non-significant increase of 53 kg ha^{-1} for MGAH and a non-significant decrease of 126 kg ha^{-1} for MTAH despite the significant increase in spring precipitation (Chapter 3). These results are also reflected in Figure 4.2a which indicates that the limitations of temperature and light interception by new spring growth were more growth restrictive for baseline climate than for CGCM2 A21 and CSIROMk2 B11 but relatively similar for HadCM3. The larger increases in MGAH compared with MTAH (Table 4.2) reflect a component of decay of the standing dead and litter fractions of the sward.

a. Melfort



b. Saskatoon

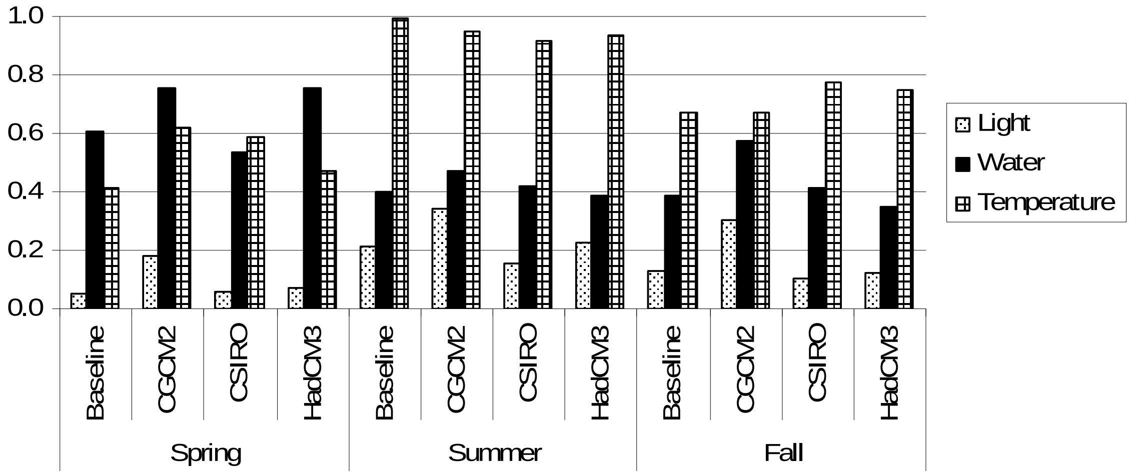


Figure 4.1 Simulated seasonal growth limits for crested wheatgrass at Melfort and Saskatoon, Saskatchewan for a soil of Sandy loam/ Sandy Clay Loam texture during a baseline time period of 30 yr (1961-1990) and projected by three climate scenarios (CGCM2 A21, CSIROMk2 B11 and HadCM3 A21) for the 30 yr time period (2040-2069). (Scale 1 indicates zero limitation to growth and scale 0 indicates total limitation).

Table 4.1 Simulated seasonal mean (±SD) available green and total (green, dead, and litter) crested wheatgrass herbage at Melfort and Saskatoon, Saskatchewan for soils of sandy loam / sandy clay loam (SL/SCL) and loam / loam (L/L) textures during a baseline 30 yr time period (1961-1990) and projected by three climate scenarios (CGCM2 A21, CSIROMk2 B11 and HadCM3 A21) for the 30 yr time period (2040-2069). Differences (P<0.05) from baseline within columns are denoted by *.

Location & Soil texture	Source	Spring		Summer		Fall	
		Green	Total	Green	Total	Green	Total
		Available Herbage (kg/ha)					
Melfort							
SL/SCL	Baseline	392±158	1623±434	1884±783	3906±990	1422±632	5027±1614
	CGCM2	695±345*	1626±501	1171±781*	3471±1543	1044±690*	3857±1949*
	CSIRO	564±312*	1563±555	1293±671*	3681±1306	1011±752*	4042±1721*
	HadCM3	348±137	1360±376	1309±523*	3350±953*	866±372*	3923±1412*
Difference + or - from baseline	CGCM2	+303	+ 3	-713	-435	-378	-1170
	CSIRO	+172	- 59	-591	-226	-410	- 986
	HadCM3	- 44	-263	-575	-556	-556	-1104
L/L	Baseline	356±154	1534±441	1745±801	3628±1002	1355±657	4724±1649
	CGCM2	621±347*	1521±643	1119±803*	3271±1637	1012±730*	3694±2077*
	CSIRO	540±321*	1530±628	1286±792*	3671±1541	1019±805	4021±2055
	HadCM3	340±141	1359±398*	1301±563*	3601±1023	874±406*	3956±1503*
Difference + or - from baseline	CGCM2	+265	-12	-626	-357	-342	-1030
	CSIRO	+184	-3	-460	43	-336	-703
	HadCM3	-16	-175	-445	-27	-481	-769
Saskatoon							
SL/SCL	Baseline	130±99	732±309	496±427	1337±887	316±241	1656±1175
	CGCM2	531±346*	1453±636*	1050±716*	3092±1491*	716±617*	3522±1878*
	CSIRO	136±128	632±307*	342±339*	1159± 821*	254±205*	1304± 1017*
	HadCM3	173±104	802±274	527±319	1643±793*	289±196	1897±972
Difference + or - from baseline	CGCM2	+401	+722	+554	+1756	+400	+1866
	CSIRO	+6	-100	-154	-177	-61	-353
	HadCM3	+43	+70	+31	+306	-27	241
L/L	Baseline	102±86	600±302	347±366	993±801	213±210	1197±1067
	CGCM2	456±329*	1304±643*	933±735*	2750±1585*	653±597*	3153±1952*
	CSIRO	75±68*	446±259*	193±232	713±595*	141±148*	793±782*
	HadCM3	143±96*	710±255*	427±280	1361±700*	551±204	1584±871*
Difference + or - from baseline	CGCM2	+354	+704	+587	+1758	+439	+1956
	CSIRO	- 27	-154	-154	- 280	- 73	- 405
	HadCM3	+ 42	+110	+ 81	+ 368	+337	+ 386

At Saskatoon, CGCM2 A21 was the only scenario to project an increase in spring MGAH and MTAH (311 and 288 kg ha^{-1}), respectively, ($P<0.05$; Table 4.2). Again, the lower increase in MTAH reflects a degree of decay of standing dead and litter. These increases can be attributed to the +3 and +5^{o}C increase in Max T and Min T and an increase in precipitation of +11% projected with CGCM2 A21 for the spring season at Saskatoon (Chapter 3). CSIROMk2 B11 and HadCM3 A21 projected decreases ($P<0.05$) of 250 and 229 kg ha^{-1}, respectively, for MGAH and 752 and 681 kg ha^{-1}, respectively, for MTAH. Even though mean Max T and Min T increased with CSIROMk2 B11 (Chapter 3), precipitation did not increase significantly, while evaporation increased. This resulted in a greater restriction of plant available water (Figure 4.2b) which reduced the spring growth of new shoot and in turn reduced the ability of the grass to capture light relative to baseline (Figure 4.2b). Similarly, even though HadCM3 A21 projected a significant increase in spring precipitation, there was a significant increase in Min T and a small increase in evaporation (Chapter 3). This resulted in a greater restriction of spring growth of new shoot which in turn reduced the ability of the grass to capture light relative to baseline (Figure 4.2b).

Production trends on the L/L texture soils were similar to those on the SL/SCL texture soil at both locations (Table 4.2).

4.3.1.2.2 Summer

On the SL/SCL soil at Melfort during summer, simulations using all three future climate scenarios projected a decrease in MGAH from the baseline value of 4302 kg ha^{-1}, but the decrease was only significant ($P<0.05$) for HadCM3 A21 (437 kg ha^{-1}). MTAH also decreased from the baseline of 5405 kg ha^{-1} but the decrease was only significant with HadCM3 A21 (441 kg ha^{-1}; $P<0.05$). The significant decreases in MGAH and MTAH with HadCM3 A21 were probably due to the reduction in available top-soil moisture projected during summer by HadCM3 A21 compared with the other climate scenarios (Table 3.4)..

At Saskatoon on the SL/SCL soil, significant decreases ($P<0.05$) in MGAH from the baseline value of 3679 kg ha^{-1} were projected by CSIROMk2 B11 (1979 kg ha^{-1}) and HadCM3 A21 (1639 kg ha^{-1}). These decreases in MGAH were probably caused by the decreases in precipitation and increases in both Max T and Min T projected by these two scenarios that resulted in greater evaporation (Chapter 3). Water was the greatest limitation to growth at Saskatoon during summer but the limitation projected by CSIROMk2 B11 and HadCM3 A21 was more severe than for the baseline or CGCM2 A21 projections (Figure 4.2b).

Projections from all three climate scenarios for MGAH and MTAH on the L/L textured soil at Melfort indicated no significant ($P>0.05$) changes from the baseline projections. Projections for the L/L soil at Saskatoon were similar to those projected for the SL/SCL soil with decreases in both MGAH and MTAH projected by CSIROMk2 B11 and HadCM3 A21 ($P<0.05$) but no change projected by CGCM2 A21 ($P>0.05$).

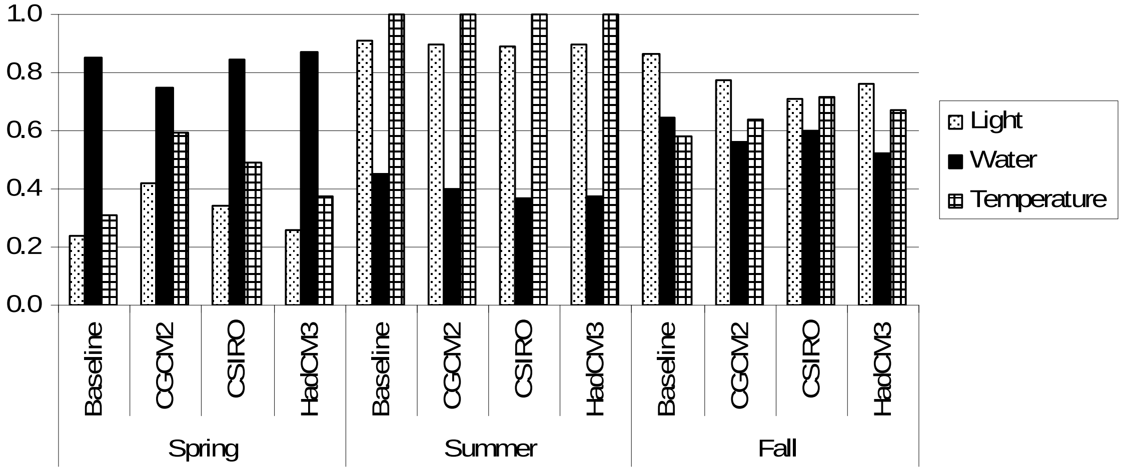
4.3.1.2.3 Fall

All climate scenarios projected decreases in fall MGAH at Melfort on the SL/SCL soil (826, 1094 and 1057 kg ha^{-1} for CGCM2 A21, CSIROMk2 B11 and HadCM3 A21, respectively). Temperature was the greatest limitation to fall growth of hybrid bromegrass during 1961-1990 but all climate scenarios projected an increase in both Max T and Min T and evaporation during 2040-2069 with little change in precipitation (Chapter 3). Consequently, water became the greatest limitation to growth during 2040-2069 (Figure 4.2a). Only HadCM3 A21 projected a significant decrease (930 kg ha^{-1}) in MTAH ($P<0.05$).

The results at Saskatoon were similar to those at Melfort for the SL/SCL soil. MGAH decreased ($P<0.05$) by 516, 1386 and 1401 kg ha^{-1} for CGCM2 A21, CSIROMk2 B11 and HadCM3 A2, respectively, from the baseline value. MTAH also decreased from the baseline value; however, the decrease was only significant ($P<0.05$) for CSIROMk2 B11 and HadCM3 A21 (2591 and 2313 kg ha^{-1}, respectively. These decreases in MGAH and MTAH were the result of water limitations (Figure 4.2a) caused by increased evaporation associated with increases in both maximum and minimum temperatures (Chapter 3) resulting in less moisture being available for plant growth during fall.

Production trends on the L/L texture soils were similar to those on the SL/SCL texture soil at both locations (Table 4.2).

a. Melfort



b. Saskatoon

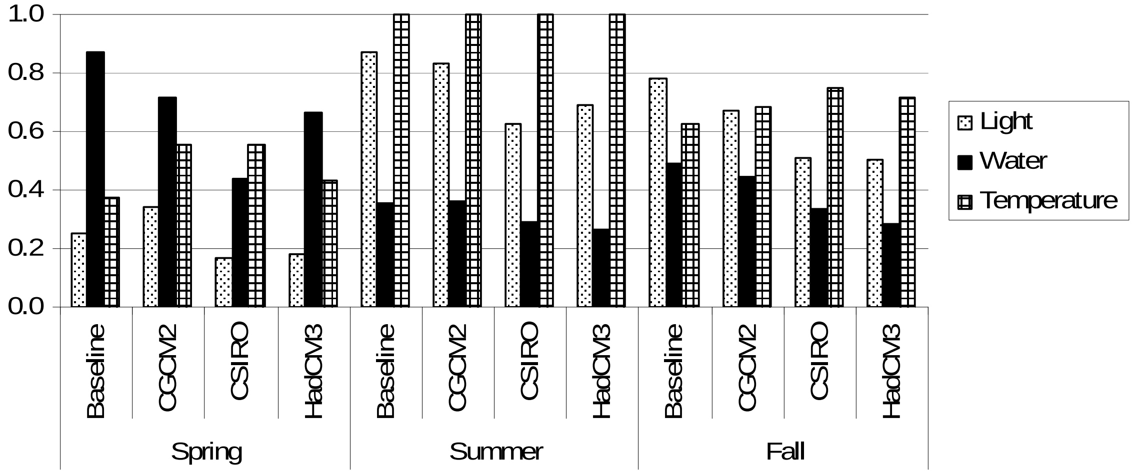


Figure 4.2 Simulated seasonal growth limits for hybrid bromegrass at Melfort and Saskatoon, Saskatchewan for a soil of Sandy loam/ Sandy Clay Loam texture during a baseline time period of 30 yr (1961-1990) and projected by three climate scenarios (CGCM2 A21, CSIROMk2 B11 and HadCM3 A21) for the 30 yr time period (2040-2069). (Scale 1 indicates zero limitation to growth and scale 0 indicates total limitation).

Table 4.2 Simulated seasonal mean (±SD) available green and total (green, dead, and litter) hybrid bromegrass herbage at Melfort and Saskatoon, Saskatchewan for soils of sandy loam / sandy clay loam (SL/SCL) and loam / loam (L/L) textures during a baseline 30 yr time period (1961-1990) and projected by three climate scenarios (CGCM2 A21, CSIROMk2 B11 and HadCM3 A21) for the 30 yr time period (2040-2069). Differences ($P<0.05$) from baseline within columns are denoted by *.

Location & Soil texture	Source	Spring		Summer		Fall	
		Green	Total	Green	Total	Green	Total
		Available Herbage (kg/ha)					
Melfort							
SL/SCL	Baseline	480±254	2092±447	4302±1167	5405±1156	3425±1242	6679±1428
	CGCM2	1125±520*	2535±672*	3960±1505	5261±1574	2599±1390*	6157±1968
	CSIRO	832±392*	2340±693*	3910±1554	5215±1567	2331±1344*	6054±2041
	HadCM3	534±211	1967±446	3865±1241*	4965±1162*	2368±760*	5749±1485*
Difference + or - from baseline	CGCM2	+645	+443	-342	-144	-826	-522
	CSIRO	+352	+248	-392	-190	-1094	-625
	HadCM3	+53	-126	-437	-441	-1057	-930
L/L	Baseline	427±243	1993±453	4106±1196	5158±1178	3305±1205	6456±779
	CGCM2	1090±532*	2483±694*	3930±1577	5210±1669	2593±1435*	6135±978
	CSIRO	804±420*	2296±758*	3883±1699	5144±1752	2340±1411*	6009±1053
	HadCM3	526±218	1958±471	3880±1262	4949±1186	2389±791*	5771±675*
Difference + or - from baseline	CGCM2	+663	+489	-176	+52	-712	-321
	CSIRO	+377	+303	-223	-14	-965	-447
	HadCM3	+ 99	-35	-226	-209	-916	-685
Saskatoon							
SL/SCL	Baseline	504±254	1868±548	3679±1270	4668±1350	2480±950	5517±1603
	CGCM2	815±566*	2156±903*	3494±1738	4646±1812	1964±1064*	5407±2283
	CSIRO	253±225*	1116±417*	1700±1069*	2478±1203*	1094±619*	2927±1388*
	HadCM3	274±171*	1187±412*	2040±1096*	2802±1179*	1079±542*	3204±1380*
Difference + or - from baseline	CGCM2	+311	+288	-185	-22	-516	-110
	CSIRO	-250	-752	-1979	-2190	-1386	-2591
	HadCM3	-229	-681	-1639	-1865	-1401	-2313
L/L	Baseline	432±259	1739±569	3421±1389	4355±1465	2367±989	5219±1735
	CGCM2	754±583*	2058±949*	3375±1851	4476±1955	1905±1075*	5242±2430
	CSIRO	202±196*	1002±392*	1475±1015*	2193±1146*	972±604*	2615±1353*
	HadCM3	223±160*	1064±398*	1793±1065*	2478±1155*	963±526*	2862±1363*
Difference + or - from baseline	CGCM2	+322	+319	-46	+122	-462	+23
	CSIRO	-230	-737	-1946	-2162	-1395	-2605
	HadCM3	-209	-675	-1628	-1877	-1404	-2357

4.3.2 Mean Digestibility and Protein Content

The trends for digestibility and protein content were similar for the SL/ SCL and L/L soil associations so only data for the SL/SCL soil are presented here.

4.3.2.1 Spring

The mean simulated seasonal digestibility and protein contents of the green and total herbage pools for crested wheatgrass and hybrid bromegrass at Melfort and Saskatoon for 1961-1990 and 2040-2069 are presented in Table 4.3.

4.3.2.1.1 Melfort

At Melfort, the mean dry matter digestibility (DMD) of the green crested wheatgrass herbage during spring 2040-2069 increased from a baseline of 71.0% to 72.7% ($P<0.05$) and mean green protein content increased from a baseline of 204.8 g kg^{-1} to 216.6 g kg^{-1} ($P<0.05$) with HadCM3 A21. CGCM2 A21 and CSIROMk2 B11 projected no change in mean green DMD; however, mean total herbage DMD increased ($P<0.05$) from the baseline of 51.6% to 54.1 and 53.3%, respectively, and mean total herbage protein increased ($P<0.05$) from a baseline of 108.2kg ha-1 to 120.6 and 116.3 kg ha^{-1},respectively. The increase in mean DMD and protein contents of the total crested wheatgrass herbage with CGCM2 A21 and CSIROMk2 B11 reflects the increase in growth of green herbage (Table 4.1) and and possibly also some removal of low digestible litter from the dead and litter pool by decay . However, there was no change in mean DMD and protein contents of the total crested wheatgrass herbage during spring with HadCM3 A21. This probably reflects the lack of change in growth of green herbage (Table 4.1) and and possibly also no change in the rate of decay of litter. The projected yields of green herbage digestible dry matter (DDM) and protein were 278 and 80 kg ha^{-}

^{1}, 487 and 139 kg ha^{-1}, 404 and 118 kg ha^{-1} and 253 and 75 kg ha^{-1}, respectively, for baseline, CGCM2 A21, CSIROMk2 B11 and HadCM3 A21.

The mean spring DMD of the green hybrid bromegrass increased ($P<0.05$) with all three scenarios from the baseline of 73.0% to 74.6% (CGCM2 A21); 74.9% (HadCM3 A21) and 76.1% (CSIROMK2 B11). Mean protein content also increased ($P<0.05$) from 221.4 g kg^{-1} to 227.0, 228.6 and 233.1 g kg^{-1}, respectively. The projected yields of green herbage digestible dry matter (DDM) and protein were 350 and 106 kg ha^{-1}, 839 and 255 kg ha^{-1}, 633 and 194 kg ha^{-1} and 399 and 122 kg ha^{-1} respectively for baseline, CGCM2 A21, CSIROMk2 B11 and HadCM3 A21. The mean DMD and protein contents of the total hybrid bromegrass herbage increased ($P<0.05$) relative to baseline with CGCM2 A21 and CSIROMk2 B11, reflecting the greater growth of green herbage relative to baseline and probably some removal of low digestible litter from the dead and litter pool by decay. There was no change in mean DMD of the total herbage with HadCM3 A21 but there was a small and significant increase in protein content, probably reflecting the small but not significant increase in spring growth with this scenario (Table 4.2).

4.3.2.1.2 Saskatoon

At Saskatoon, both CGCM2 A21 (71.1%) and CSIROMk2 B11 (70.2%) projected a decrease ($P<0.05$) in mean DMD of green crested wheatgrass relative to baseline (72.5%) while HadCM3 A21 projected no change (Table 4.3; $P>0.05$). Although CGCM2 projected a decrease in mean green DMD, the change in mean green protein content from 212.6 to 205.4g kg^{-1} was not significant. In contrast, CSIROMk2 B11 projected a significant decline ($P<0.05$) in both DMD and protein content of green crested wheatgrass herbage to 70.2 % and 201.0 g kg^{-1}, respectively while HadCM3 A21 projected no change in either DMD or protein content. The projected yields of green DDM and protein were 94 and 28 kg ha^{-1}, 378 and 109 kg ha^{-1}, 95 and 27 kg ha^{-1} and 125 and 37 kg ha^{-1} respectively for baseline, CGCM2 A21, CSIROMk2 B11 and HadCM3 A21. These projections represent large differences between CGCM2 A21 and the other scenarios in available nutrients from crested wheatgrass in spring. Changes in DMD and protein content of the total crested wheatgrass herbage reflect the changes in growth of green herbage and decay of litter as described for Melfort.

Projections for hybrid bromegrass indicated no significant change in either mean green DMD or green protein content relative to baseline (Table 4.3). However, because of the increase relative to baseline of available green hybrid bromegrass with CGCM2 A21 and the decrease relative to baseline with CSIROMk2 B11 and HadCM3 A21 (Table 4.2), there were large projected differences in the yields of green herbage DDM and protein between the three climate scenarios (618 and 167 kg ha^{-1} respectively for CGCM2 A21; 187 and 51 kg ha^{-1} respectively for CSIROMk2 B11 and 207 and 54 kg ha^{-1} respectively for HadCM3 A21) and in relation to baseline (365 and 115 kg ha^{-1} respectively).

4.3.2.2 Summer

4.3.2.2.1 Melfort

CSIROMk2 B11 projected a decrease from baseline in mean DMD of green crested wheatgrass herbage during summer at Melfort on the SL/SCL soil ($P<0.05$) but no change in protein content. The other two scenarios did not project any changes in DMD or protein content of green crested wheatgrass herbage. However, the large decreases in summer yield of green crested wheatgrass herbage (Table 4.1) resulted in large decreases in the yields of green DDM and protein from 1219 and 327 kg ha^{-1} respectively for baseline to 748 and 199 kg ha^{-1} for CGCM2 A21, 826 and 219 kg ha^{-1} for CSIROMk2 B11 and 850 and 229 kg ha^{-1} for HadCM3 A21.

All climate scenarios projected decreases ($P<0.05$) in mean DMD of green hybrid bromegrass during summer from the baseline of 72.7% to 67.6, 68.8 and 70.5% for CGCM2 A21, CSIROMk2 B11 and HadCM3 A21 respectively. All scenarios projected a decrease in mean green protein, however, only the CGCM2 (200.1 g kg^{-1}) and CSIRO (204.5 g kg^{-1}) were significantly different ($P<0.05$) from baseline (218.7 g kg^{-1}). HadCM3 A21 projected the least change in mean green DMD and mean green protein content, however, it projected the greatest decrease in mean green DDM. As a result, the baseline yields of green DDM and protein (3128 and 941 kg ha^{-1} respectively) were greater than the projected yields of 2677 and 792 kg ha^{-1} for CGCM2 A21, 2690 and 799 kg ha^{-1} for CSIROMk2 B11, and 2725 and 814 kg ha^{-1} for HadCM3 A21.

4.3.2.2.2 Saskatoon

At Saskatoon, CSIROMk2 B11 was the only scenario to project significant, though small, increases in mean green DMD from baseline of 64.4 to 65.0% and mean green protein content from 172.2 to 175.3 g kg^{-1} ($P<0.05$). However, the greater availability of green crested wheatgrass herbage projected by CGCM2 A21 relative to baseline and the other two climate scenarios resulted in a greater availability of DDM and protein (671 and 178 kg ha^{-1} respectively compared with 319 and 85 kg ha^{-1} respectively for baseline, 222 and 60 kg ha^{-1} respectively for CSIROMk2 B11, and 341 and 91 kg ha^{-1} respectively for HadCM3 A21).

All three climate scenarios projected significant decreases relative to the baseline value of 71.5% for mean green DMD of hybrid bromegrass during summer, ranging from 69.2% for HadCM3 A21, 68.9% for CSIROMk2 B11 and 68.5% for CGCM2 A21 ($P<0.05$). Mean green protein content also significantly ($P<0.05$) decreased from a baseline value of 214.0 g kg^{-1} with all three scenarios (205.9 g kg^{-1} for HadCM3 A21, 205.1 for CSIROMk2 B11 and 203.0 g kg^{-1} for CGCM2 A21). CGCM2 A21 projected no change from baseline for MGAH but significant decreases were projected by CSIROMk2 B11 and HadCM3 A21 (Table 4.2). As a result, the summer yield of green DDM and protein of hybrid bromegrass at Saskatoon were 2630 and 787 kg ha^{-1} respectively for baseline, 2393 and 709 kg ha^{-1} respectively for CGCM2 A21, 1171 and 349 kg ha^{-1} respectively for CSIROMk2 B11 and 1412 and 420 kg ha^{-1} respectively for HadCM3 A21. Thus all three scenarios projected a decline in available nutrients during summer.

4.3.2.3 Fall

4.3.2.3.1 Melfort

All three climate scenarios projected decreases in mean DMD of green crested wheatgrass herbage during fall relative to baseline (68.2%) at Melfort on the SL/SCL soil, however, only the CGCM2 A21 and HadCM3 A21 scenarios projected a significant decrease from the baseline to 64.8 and 65.45, respectively ($P<0.05$). All three scenarios projected a decrease in mean green protein content from a baseline of 190.8 to 184.8 (CSIROMk2 B11); 177.7 HadCM3 and 174.1 kg ha^{-1} (CGCM2 A21) ($P<0.05$). The projected yields of green DDM and protein were 969 and 271 kg ha^{-1} respectively for baseline, 677 and 182 kg ha^{-1} respectively for CGCM2 A21, 677 and 186 kg ha^{-1} respectively for CSIROMk2 B11, 566 and 153 kg ha^{-1} respectively for HadCM3 A21.

The projected decreases in yields of green DDM and protein reflect not only a reduction in herbage available but also a reduction in the quality of the green yield in comparison to the baseline.

CSIROMk2 B11 and HadCM3 A21 scenarios projected a decrease ($P<0.05$) in mean DMD of green hybrid bromegrass during the fall from the baseline of 65.7% to 64.1 and 63% respectively and mean green protein content from 193.8 to 189.2 and 184.7 g kg^{-1} respectively. Both CSIROMk2 B11 and HadCM3 A21 also projected the greatest decrease in MGAH. As a result, the projected yields of green DDM and protein were 2250 and 664 kg ha^{-1} respectively for baseline, 1691 and 500 kg ha^{-1} respectively for CGCM2 A21, 1494 and 441 kg ha^{-1} respectively for CSIROMk2 B11 and 1492 and 437 kg ha^{-1} respectively for HadCM3 A21.

4.3.2.3.2 Saskatoon

At Saskatoon, all three scenarios projected a decreases in mean green DMD of crested wheatgrass during fall from a baseline of 66.6 to 64.4% for CGCM2 A21, 64.0% for CSIROMk2 B11 and 64.2% for HadCM3 and mean green protein content from a baseline of 190.8 to 174.1 g kg^{-1} for CGCM2 A21, 184.8 g kg^{-1} for CSIROMk2 B11 and 177.1 g kg^{-1} for HadCM3 ($P<0.05$). However, the greater availability of green crested wheatgrass herbage projected by CGCM2 A21 relative to baseline and the other two climate scenarios resulted in a greater availability of DDM and protein (210 and 54 g ha^{-1} respectively for baseline and 461 and 123 g ha^{-1} respectively for CGCM2 A21) compared to 163 and 43 g ha^{-1} respectively for CSIROMK2 B11 and 186 and 43 g ha^{-1} respectively for HadCM3 A21.

Mean green DMD of hybrid bromegrass during fall increased ($P<0.05$) with the CSIROMk2 B11 scenario from the baseline of 63.6% to 64.5% as did the mean green protein content (from 186.6 g kg^{-1} to 190.1 g kg^{-1}) but there was no change for either CGCM2 A21 or HadCM3 A21. However, because of the large reduction in available green herbage relative to baseline projected by all three scenarios during fall, the yield of green DDM and protein was greatly reduced with all three scenarios, in particular with CSIROMk2 B11 and HadCM3 A21. The fall yields of green DDM and protein of hybrid bromegrass at Saskatoon were 1577 and 463 kg ha^{-1} respectively, for baseline, 1255 and 369 kg ha^{-1} respectively for CGCM2 A21, 706 and 208 kg ha^{-1} respectively for CSIROMk2 B11 and 673 and 197 kg ha^{-1} respectively, for HadCM3 A21.

Table 4.3 Simulated seasonal mean digestibility (±SD) and protein content (±SD) of dry matter green and total (green, dead, and litter) crested wheatgrass (CWG) and hybrid bromegrass (HBG) herbage at Melfort and Saskatoon, Saskatchewan for soils of sandy loam / sandy clay loam (SL/SCL) texture during a baseline 30 yr time period (1961-1990) and projected by three climate scenarios (CGCM2 A21, CSIROMk2 B11 and HadCM3 A21) for the 30 yr time period (2040-2069). Differences (P<0.05) from baseline within columns are denoted by *.

Location &	Source	Spring		Summer		Fall	
Soil texture		Green	Total	Green	Total	Green	Total
		Digestibility DM (%)					
Melfort SL/SCL	Baseline	71.0±4.5	51.6±1.8	64.7±1.4	58.1±2.4	68.2±2.4	52.7±2
CWG	CGCM2	70.1±2.9	54.1±3.2*	63.9±2.2	54.2±3.3*	64.8±3.5*	51.3±2.7
	CSIRO	71.7±3.4	53.3±2.6*	63.9±2.1*	55.4±3.2*	67.0±3.6	51.4±2.8*
	HadCM3	72.7±3.1*	51.1±1.9	64.9±1.5	56.5±2.7*	65.4±2.9*	50.7±1.6
HBG	Baseline	73.0±3.2	56.9±1.8	72.7±1.1	67.4±2.1	65.7±2.1	60.5±2.4
	CGCM2	74.6±2.1*	59.6±3.0*	67.6±2.8*	63.6±3.4*	65.1±2.8	57.5±2.8*
	CSIRO	76.1±2.1*	58.0±2.0*	68.8±2.2*	64.3±3.4*	64.1±3.2*	56.8±3.0*
	HadCM3	74.9±3.0*	56.2±1.6	70.5±1.3*	65.6±2.7*	63.0±2.1*	56.9±1.7*
Saskatoon SL/SCL	Baseline	72.5±3.4	50.6.±2.0	64.4±1.6	56.7±3.0	66.6±3.0	50.8±1.8
CWG	CGCM2	71.1±3.1*	52.1±3.6*	63.9±2.0	54.4±3.9*	64.4±3.4*	50.0±2.4*
	CSIRO	70.2±4.0*	48.1±3.5*	65.0±1.7*	51.2±4.4*	64.0±2.8*	49.0±3.5*
	HadCM3	72.4±2.6	48.6±2.7*	64.7±2.3	53.6±3.9*	64.2±4.2*	48.7±2.3*
HBG	Baseline	74.9±2.9	56.3±2.0	71.5±1.4	66.2±2.9	63.6±2.7	58.3±2.2
	CGCM2	75.8±1.8	57.5±3.5*	68.5±2.6*	63.5±4.4*	63.9±3.5	56.4±2.4*
	CSIRO	74.0±3.3	55.0±2.9*	68.9±1.8*	62.0±3.7*	64.5±3.2*	56.8±2.6*
	HadCM3	75.6±2.5	54.5±2.8*	69.2±1.9*	62.8±4.5*	62.4±3.2	55.1±2.6*
Melfort		Protein Content (g kg^{-1})					
SL/SCL	Baseline	204.8±22.9	108.2±9.4	173.6±6.9	140.4±12.2	190.8±12.3	113.7±10.0
CWG	CGCM2	200.7±14.7	120.6±16.1*	169.7±11.3	121.0±17.0*	174.1±17.8*	106.3±13.6*
	CSIRO	208.4±17.1	116.3±13.4*	169.4±10.9	127.0±16.5*	184.8±18.3*	106.3±13.6*
	HadCM3	216.6±15.6*	105.6±9.7	174.7±7.6	132.4±13.5*	177.1±14.7*	103.5±8.2*
HBG	Baseline	221.4±12.7	165.8± 6.7	218.7±4.2	199.9±7.5	193.8±7.9	175.2±8.3
	CGCM2	227.0±8.4*	174.4±10.8*	200.1±10.4*	186.1±12.2*	192.4±10.3	165.0±9.9*
	CSIRO	233.1±8.4*	169.1±7.4*	204.5±8.3*	188.5±12.3*	189.2±11.6	162.7±10.5*
	HadCM3	228.6±12.2*	162.7± 6.0*	210.5±4.9	193.5±9.7*	184.7±7.9*	162.7±5.9*
Saskatoon SL/SCL CWG	Baseline	212.6±17.2	103.1±10.1	172.2±7.9	133.6±15.2	183.0±15.1	103.9±9.1
	CGCM2	205.4±15.8	110.6±18.1*	169.5±10.3	122.1±19.9*	172.0±17.1*	100.2±12.2*
	CSIRO	201.0±20.6*	90.3±18.1*	175.2±8.9*	106.1±22.3*	170.2±14.3*	95.0±18.0*
	HadCM3	211.9±13.4	93.2±13.5*	173.6±11.7	117.9±20.0*	170.9±21.3*	93.7±11.7*
HBG	Baseline	228.5±11.9	163.2±7.4	214.0±5.4	195.6±10.6	186.6±10.0	167.6±7.9
	CGCM2	231.7±7.4	166.9±12.7	203.0±9.7*	185.7±15.7*	188.0±12.7	161.2±8.6*
	CSIRO	225.5±13.3	157.7±10.7*	205.1±6.7*	180.6±13.1*	190.1±11.5*	162.2±9.1*
	HadCM3	231.3±10.4	157.7±10.7*	205.9±7.0*	183.4±16.3*	182.8±11.8	156.5±9.2*

4.4 Conclusion

Both the quantity and quality of the mean available herbage throughout the three seasons of growth were affected by climate change. The general trend was for CGCM2 A21 and CSIROMk2 B11 to increase the quantity and quality of the green herbage relative to baseline during spring for both grasses at Melfort while HadCM3 A21 projected little change from baseline in the quantity but an increase in quality. At Saskatoon this increase was restricted to CGCM2 A21 only and the effect continued through summer and fall for the crested wheatgrass but not the hybrid bromegrass. Nevertheless, the projected yields of green DDM and protein from crested wheatgrass were lower than hybrid bromegrass with all three climate change scenarios at both locations suggesting that hybrid bromegrass may be more adaptable to climate change.

This study also suggests that, when considering responses of tame forage species to climate change, soil texture should be considered. The SL/SCL textured soil tended to have greater production during the baseline period (1961-1990) and during 2040-2069 however the negative impact of climate during 2040-2069 was less for the L/L textured soil than the SL/SCL soil.

It is concluded that hybrid bromegrass may be better able to adapt to climate change in comparison to crested wheatgrass because it is more tolerant of increased temperature than crested wheatgrass. The results of this study suggest that climate change may affect the productivity of cattle grazing these pastures. This will be reported in Chapter 5.

CHAPTER 5

5.0 SIMULATED EFFECT OF CLIMATE CHANGE ON INTAKE AND PRODUCTION OF STEERS GRAZING TWO GRASS PASTURES AT TWO LOCATIONS IN SASKATCHEWAN, CANADA.

5.1 Introduction

Since 1990, when there was a marked increase in climate change research, the possible effects of changes in climate have become more widely accepted. However, the likely response of pasture and cattle production to changing climate in Saskatchewan and the Canadian Prairies has been relatively unexplored.

The number of cattle and calves on Saskatchewan farms was 2.93 million in 2007 and since 2006 steer numbers have increased by 8% (Saskatchewan Agriculture and Food, 2007). Since 1983, cattle numbers have steadily increased in Saskatchewan (Saskatchewan Agriculture and Food, 2007). Much of this increase can be related to permanent cover programs in Saskatchewan that have resulted in the conversion of more than 200,000 ha of marginal land back to permanent cover from 1986 to 1996, of which 64% is being used for grazing (Vaisey et al., 1996).

Crested wheat grass (*Agropyron cristatum*) has been the most commonly sown grass on the Canadian Prairies. In Saskatchewan and Alberta there are 1.5 million ha of crested wheatgrass (Henderson, 2005). During the 1930s and 1960s many of the native pasture areas were tilled and reseeded with introduced species such as crested wheatgrass (Rogler and Lorenz, 1983; DuPuit, 1986) which is a grass that is able to withstand severe droughts (Coulman et al., 1999). However, newer species such as Hybrid brome grass that is a cross between smooth brome grass (*Bromus inermis*) and meadow brome grass (*Bromus riparius*) may be more productive than crested wheatgrass (Knowles and Baron, 1990). This species is relatively new and not yet well documented in the literature (Ferdinandez and Coulman, 2001).

The simulated response to changing climate of ungrazed old standard grasses such as crested wheatgrass and new grasses such as hybrid brome grass has been reported (Chapter 3) but the simulated effects of climate change on cattle grazing these grasses have not been studied. Several crop models have been used to predict responses of crop species to climate change (Ewert et al., 2007; Long et al., 2006; and IPCC, 2001b). Baker et al. (1993) and Bolortsetseg and Tuvaansuren (1996) used the SPUR2 model and predicted that the impact on unspecified rangeland and tame pasture species on United States of America and Mongolian grasslands would be minimal. However, results presented in Chapters 3 and 4 suggest that the effects of climate change in Saskatchewan would vary depending on the model used to predict climate change and that; in general, spring productivity of tame pasture will increase while productivity during summer and fall will decrease. Chapter 4 also predicted that the effects of climate change on crested wheatgrass may be more severe than those on hybrid bromegrass.

The present study used the GrassGro decision support tool (Moore et al., 1997) which has been modified for use in Canada (Cohen et al., 2003) to investigate the impacts of three different climate change scenarios on the productivity of steers grazing crested wheatgrass and hybrid bromegrass at two locations in Saskatchewan.

5.2 Methodology

5.2.1 Sites, Climate, Pastures Animals and Model

Two sites in Saskatchewan were chosen: Melfort (52 º 49’ N; 104 º 36’ W; 480 m altitude) and Saskatoon (52 º 10’ N; 106 º 41’ W; 501 m altitude). Historical climate data for 1961-1990 (baseline) were obtained from records at the Agriculture and Agri-Food Canada Research Stations at Melfort and Saskatchewan Research Council at Saskatoon. Future climate was predicted for three 30-yr periods: the 2020s (2010-2039), the 2050s (2040-2069) and the 2080s (2070-2099) using three climate change scenarios: The Canadian Climate Centre Model (CGCM2a21) of the second generation (3.75° x 3.75° resolution grid about 400 km) (Flato and Boer, 2001); Hadley Climate Model (HadCM3a21) of the third generation (2.5° x 3.75°) (Gordon, 2000; Pope et al., 2000); Commonwealth Scientific and Industrial Research Organization (CSIROMk2 B11 ; 5.6° x 3.2°) (Hirst et al., 1996; Hirst et al., 2000) as described in Chapter 3.

The GrassGro decision support tool (Moore et al., 1997) was used for all simulations as described in Chapter 3. The pastures used in the simulations were crested wheatgrass (*Agropyron cristatum*) and hybrid brome grass (*Bromus riparius* x *Bromus inermis*) and the steers were assumed to be medium framed British breeds (Herford, Angus, Shorthorn) with a mature weight of 500 kg. Initial liveweights of the steers were set at 310 kg each year, stocking density was set at 2 steers ha^{-1} and a turn out date of April 15 was chosen in accordance with the predictions made in Chapter 3 that suggested that climate change would stimulate earlier growth of these grasses in spring than would be normal for 1961-1990. Steers were assumed to be taken off the pastures on October 31 each year. GrassGro was configured to provide a supplement of good quality grass/alfalfa hay (dry matter digestibility 60%; crude protein 160 g kg^{-1} dry matter) when body condition score fell below 2.0 (scale 1-5).

5.2.2 Statistical Analyses

Mean dry matter intakes of herbage and supplement, metabolizable energy intake, average daily gain and live-weight of steers from April 15 to October 31 as predicted with each of the three climate change scenarios and each of the three 30-yr periods were compared with baseline simulations using the two-tailed “t”-test (Analytical Software, 2000).

5.3 Results and Discussion

5.3.1 Intakes and Liveweights of Steers

Mean daily dry matter intakes (DMI) of herbage and supplement by steers grazing crested wheatgrass (CWG) and hybrid bromegrass (HBG) at Melfort and Saskatoon during 1961-1990 and the 2020s, 2050s and 2080s are presented in Table 5.1. Table 5.2 presents the metabolizable energy intakes (MEI) of herbage and supplement and total MEI of the steers. Table 5.3 presents the average daily gains (ADG) of the steers and Table 5.4 presents the average number (and range) of days that supplement was required each year for the steers to maintain a body condition score (BCS) of 2.0. Figures 5.1 and 5.2 present the mean daily liveweight curves of the steers at Melfort and Saskatoon respectively during the four time periods studied.

Table 5.1 Simulated mean (± SD) DM intake of herbage, supplement and total DM intake by steers grazing crested wheatgrass (CWG) and hybrid bromegrass (HBG) at Melfort and Saskatoon, Saskatchewan during a baseline 30 yr time period (1961-1990) and projected by three climate scenarios (CGCM2 A21, CSIROMk2 B11 and HadCM3 A21) for three 30 yr time periods. Differences (P<0.05) from baseline within columns are denoted by *.

		Melfort				**Saskatoon**			
		Baseline	**CGCM2**	**CSIRO**	**HadCM3**	**Baseline**	**CGCM2**	**CSIRO**	**HadCM3**
Mean herbage intake (kg DM steer^{-1} d^{-1})									
CWG	Baseline (1961-1990)	7.5±1.5				2.6±1.8			
	2020s		7.0±1.0*	7.6±1.3	7.0±1.1*		5.7±1.5*	2.3±1.8	3.4±1.9*
	2050s		6.2±2.3*	6.5±1.6*	6.2±1.4*		5.3±2.6*	2.3±1.8	3.1±1.7
	2080s		6.1±2.1*	5.8±1.9*	6.6±1.5*		5.2±2.3*	1.7±1.4*	3.0±1.7
HBG	Baseline (1961-1990)	9.5±0.7				4.6±2.6			
	2020s		9.4±0.4	9.5±0.5	9.5±0.4		9.0±0.8*	4.7±2.7	6.1±2.5*
	2050s		9.1±0.9	9.0±1.0*	9.2±0.7*		8.0±2.4*	4.3±2.6	5.6±2.5*
	2080s		9.1±0.8*	8.4±1.5*	9.3±0.4		8.4±1.7*	3.6±2.3*	5.4±2.4*
Mean supplement intake (kg DM steer^{-1} d^{-1})									
CWG	Baseline (1961-1990)	0.1±0.5				2.7±1.4			
	2020s		0.1±0.3	0.1±0.4	0.1±0.3		0.6±0.8*	2.9±1.3	2.0±1.5*
	2050s		0.8±1.1*	0.4±0.7*	0.4±0.8		1.1±1.4*	2.8±1.3	2.3±1.2
	2080s		0.7±0.9*	0.8±0.9*	0.3±0.5		1.2±1.3*	3.2±1.0*	2.4±1.3
HBG	Baseline (1961-1990)	0.0±0.0							
	2020s		0.0±0.0	0.0±0.0	0.0±0.0	1.2±1.1	0.0±0.0*	1.1±1.2	0.7±1.1*
	2050s		0.0±0.0	0.0±0.1	0.0±0.1		0.3±0.7*	1.3±1.3	0.8±1.2
	2080s		0.0±0.0	0.1±0.4	0.0±0.0		0.1±0.4*	1.6±1.3*	0.9±1.0
Mean total intake(kg DM steer^{-1} d^{-1})									
CWG	Baseline (1961-1990)	7.7±1.2				5.3±0.6			
	2020s		7.1±0.8*	7.7±1.1	7.1±0.9*		6.4±0.9*	5.2±0.5	5.4±0.5
	2050s		7.0±1.4*	6.9±1.1*	6.6±0.9*		6.4±1.4*	5.1±0.6*	5.4±0.5
	2080s		6.8±1.3*	6.6±1.1*	6.9±1.0*		6.4±1.1*	4.9±0.5*	5.4±0.5
HBG	Baseline (1961-1990)	9.5±0.7				5.8±1.6			
	2020s		9.4±0.4	9.5±0.5	9.5±0.4		9.0±0.8*	5.8±1.6	6.8±1.6*
	2050s		9.1±0.9	9.0±1.0*	9.2±0.6*		8.3±1.9*	5.6±1.4	6.4±1.5*
	2080s		9.1±0.8*	8.5±1.2*	9.3±0.4		8.5±1.4*	5.2±1.1*	6.3±1.5*

5.3.1.1 Melfort

At Melfort, the mean DMI of the CWG herbage by the steers was reduced during all projected time periods and climate scenarios ($P<0.05$) relative to the baseline years with the exception of the CSIROMk2 B11 scenario during the 2020s. Concurrently, the DMI of supplement increased or remained relatively constant. The net result was a reduction ($P<0.05$) in total DMI (Table 5.1), total MEI (Table 5.2) and ADG of the steers (Table 5.3) relative to baseline with the exception of CSIROMk2 B11 during the 2020s. A similar pattern was followed with steers grazing HBG except that the reduced intakes and ADGs did not occur until the 2050s.

The mean daily liveweight curves for the steers at Melfort (Figure 5.1) clearly indicate the superiority of HBG over CWG. Figure 5.1 also indicates that, during the baseline years, the steers grazing CWG continued to grow through summer and fall, albeit at a reduced rate relative to spring, but during the 2020s there was little summer and fall growth, except for the CSIROMk2 B11 scenario. During the 2050s and 2080s the steers lost weight between June and October, except for CGCM2 A21 when they maintained weight through summer and fall. This reflects the suggestion that summer temperatures will become too hot for sustained growth of CWG (Chapter 4) and may result in poor liveweight performance of grazing livestock.

The number of days supplement was required was also less for HBG than for CWG (Table 5.4). On average, supplement was required by steers grazing the HBG on only one day each year during the 2080s (range 0-27 d) when mean DMI of HBG dropped below 9 kg DM steer^{-1} with the CSIROMk2 B11 scenario. Supplement was not required during any other time period with any of the climate change scenarios. In comparison, steers grazing CWG required supplementation during the baseline years and all three future time-periods to maintain a BCS of 2.0, although there were individual years when no supplement was required. It should also be noted that the average number of days that supplement was required by steers grazing CWG increased during each 30-yr period for each of the three climate scenarios.

5.3.1.2 Saskatoon

At Saskatoon, the mean DMI (Table 5.1) and MEI (Table 5.2) of the CWG herbage by the steers increased ($P<0.05$) relative to baseline during all three time periods for CGCM2 A21, during the 2020s with HadCM3 A21 but did not change significantly during the 2050s and 2080s. However, with the CSIROMk2 B11 scenario they remained unchanged during the 2020s and 2050s and decreased ($P<0.05$) during the 2080s. Concurrently, the DMI and MEI of supplement decreased with CGCM2 A21 during all three time periods and for HadCM3 A21 during the 2020s but remained unchanged during the 2050s and 2080s while for CSIROMk2 B11 they remained unchanged during the 2020s and 2050s but increased ($P<0.05$) during the 2080s. This caused an increase ($P<0.05$) in total DMI (Table 5.1), total MEI (Table 5.2) and ADG (Table 5.3) of the steers with the CGCM2 A21 scenario, no change with the HadCM3 A21 and scenario and with the CSIROMk2 B11 scenario during the 2020s and 2050s but a decrease ($P<0.05$) during the 2080s. The net result was a projected increase ($P<0.05$) in ADG of steers (Table 5.3) and a large decrease in the number of days that the steers required supplement (Table 5.4) with the CGCM2 A21 scenario but no change in ADG of steers with the other two scenarios and a relatively small change in the number of days that the steers required supplement with the HadCM3 A21 (decrease) and CSIROMk2 B11 (increase).

A similar pattern was followed with steers grazing HBG except that the mean herbage DMI and MEI, total DMI and MEI and ADG of the steers were increased ($P<0.05$) with both the CGCM2 A21 and the HadCM3 A21 scenarios during all three time periods. In addition, the number of days that steers required supplementary feeding was reduced with all scenarios and time periods.

The superior productivity of the HBG when compared with CWG at Saskatoon is also clearly illustrated in Figure 5.2. Figure 5.2 also indicates that, during the baseline years, the steers grazing CWG reached a peak liveweight during early summer and maintained growth for the rest of the season, but during the 2020s all climate scenarios predicted that the steers would lose weight during spring and not recover their initial liveweight for the rest of the season. During the 2050s and 2080s the steers grazing CWG gained a small amount of weight until July and then barely maintained or lost a small amount of weight during the remainder of the season. In comparison, steers grazing CWG reached their peak liveweight later in the grazing season during the baseline years than during any subsequent time period. This, together with the results from Melfort supports the suggestion that climate change will cause summer temperatures to become too hot for sustained growth of CWG (as indicated in Chapter 4) and that this will result in poor liveweight production of grazing livestock .

The steers grazing HBG at Saskatoon during the baseline years began to grow later in the season in comparison to those grazing CWG, but during all future time periods the CGCM2 A21 scenario predicted that these steers would continue to gain weight throughout the grazing season, while the HadCM3 A21 scenario predicted peak liveweight would be reached in August with little growth thereafter, similar to the baseline years, and the CSIROMk2 B11 predicted an earlier and reduced peak in comparison to the baseline years that decreased with each 30-yr period.

The average number of days each year that supplement was required was also less for HBG than for CWG (Table 5.4). On average, supplement was required by steers grazing HBG for 77 days each year (range 0-184 d) during the baseline years. During the 2020s and 2050s both the CSIROMk2 B11 and HadCM3 A21 scenarios required supplement to be fed for 42 days each year while no supplement was required with the CGCM2 A21 scenario during the 2020s and was required on only 16 days each year during the 2050s and 6 days each year during the 2080s. In comparison, steers grazing CWG required supplementation at some time during all four time-periods, although, as for Melfort, there were individual years when no supplement was required. It should also be noted that the average number of days each year that supplement was required increased during each 30-yr period for each of the three climate scenarios.

Table 5.2 Simulated metabolizable energy intake (MEI ± SD) of herbage and supplement by steers grazing crested wheatgrass (CWG) and hybrid bromegrass (HBG) at Melfort and Saskatoon, Saskatchewan during a baseline 30 yr time period (1961-1990) and projected by three climate change scenarios (CGCM2 A21, CSIROMk2 B11 and HadCM3 A21) for three 30 yr time periods. Differences ($P<0.05$) from baseline within columns are denoted by *.

		Melfort				**Saskatoon**			
		Baseline	**CGCM2**	**CSIRO**	**HadCM3**	**Baseline**	**CGCM2**	**CSIRO**	**HadCM3**
MEI of herbage (MJ head^{-1}d^{-1})									
CWG	Baseline (1961-1990)	76.8±19.0				22.8±17.8			
	2020s		68.4±13.7*	77.7±18	69.5±14.5*		54.9±17.6*	20.2±16.9	31.1±18.4*
	2050s		61.6±27.1*	63.9±20*	59.9±16.8*		51.6±28.7*	20.1±17.2	27.5±15.7
	2080s		59.5±24.7*	55.4±22*	64.9±17.8*		49.2±25.3*	14.6±12.6*	26.1±16.9
HBG	Baseline (1961-1990)	106.4±9.7				47.9±28.1			
	2020s		104.4±6.4	106.2±9.0	105.2±6.3		97.4±11.6*	48.3±28.6	62.9±28.1*
	2050s		100.1±12.9*	98.4±14.5*	100.2±9.8*		86.9±28.6*	43.7±27.3	57.5±27.1*
	2080s		99.5±12.6*	89.6±19.6*	102.9±6.8*		90.2±21.1*	35.5±24.3*	55.3±26.2*
MEI of supplement (MJ head^{-1}d^{-1})									
CWG	Baseline (1961-1990)	1.3±4.0				24.3±12.3			
	2020s		1.1±2.5	1.0±3.6	1.0±2.4		5.5±7.1*	25.7±11.7	18.1±13.2*
	2050s		7.0±10*	3.7±6.1*	3.4±6.8		10.3±12.9*	25.3±11.6	20.6±11.1
	2080s		6.5±8.5*	7.2±8.1*	2.8±4.7		10.6±11.5*	29.0±8.8*	21.9±12.0
HBG	Baseline (1961-1990)	0.0±0.0				10.7±10.1			
	2020s		0.0±0.0	0.0±0.0	0.0±0.0		0.0±0.0*	10.0±10.7	6.4±9.5*
	2050s		0.0±0.0	0.1±0.5	0.1±0.5		2.3±6.0*	11.9±12.0	7.0±10.8
	2080s		0.0±0.0	1.0±3.8	0.0±0.0		0.8±3.2*	14.7±12.1*	7.7±9.3
Total MEI intake (MJ head^{-1}d^{-1})									
CWG	Baseline (1961-1990)	78.1±16.4				47.1±6.0			
	2020s		69.5±12.2	78.7±16.1	70.5±13.3		60.5±11.5*	45.9±5.7	49.1±5.7*
	2050s		68.5±19.0	67.6±15.8	63.3±12.2		61.8±17.8*	45.4±6.0*	48.2±5.1
	2080s		66.0±17.9	62.6±15.5	67.6±14.2		59.8±15.3*	43.6±4.4*	48.0±5.3
HBG	Baseline (1961-1990)	106.4±9.7				58.5±19.1			
	2020s		104.4±6.4	106.2±9.0	105.2±6.3		97.4±11.6*	58.3±19.2	69.3±19.8*
	2050s		100.1±12.9*	98.5±14.3*	100.3±9.5*		89.2±23.7*	55.6±16.6	64.6±18.1*
	2080s		99.5±12.6*	90.6±17.0*	102.9±6.8*		91.0±19.1*	50.2±13.1*	63.0±18.2*

Table 5.3 Simulated average daily gains (± SD) by steers grazing crested wheatgrass (CWG) and hybrid bromegrass (HBG) at Melfort and Saskatoon, Saskatchewan during a baseline 30 yr time period (1961-1990) and projected by three climate change scenarios (CGCM2 A21, CSIROMk2 B11 and HadCM3 A21) for three 30 yr time periods . Differences ($P<0.05$) from baseline within columns are denoted by *.

		Melfort				**Saskatoon**			
		Baseline	**CGCM2**	**CSIRO**	**HadCM3**	**Baseline**	**CGCM2**	**CSIRO**	**HadCM3**
Average daily gains (kg d^{-1})									
CWG	Baseline 1961-1990	0.3±0.3				-0.1±0.03			
	2020s		0.2±0.23*	0.3±0.29	0.2±0.24*		0.0±0.2*	-0.1±0.0	-0.1±0.3
	2050s		0.2±0.32*	0.1±0.28*	0.1±0.22*		0.1±0.3*	-0.1±0.0	-0.1±0.3
	2080s		0.1±0.30*	0.1±0.26*	0.1±0.25*		0.0±0.2*	-0.1±0.0	-0.1±0.3
HBG	Baseline 1961-1990	0.8±0.19				0.07±0.3			
	2020s		0.8±0.12	0.8±0.17	0.8±0.12		0.7±0.2*	0.1±0.3	0.2±0.3*
	2050s		0.7±0.25*	0.7±0.28*	0.7±0.18*		0.6±0.4*	0.0±0.2	0.1±0.3*
	2080s		0.7±0.24*	0.5±0.32*	0.8±0.13		0.6±0.4*	-0.1±0.2*	0.1±0.2*

Table 5.4 Average number of days (range) that steers required supplemental hay to maintain a body condition score of 2.0 while grazing crested wheatgrass (CWG) and hybrid bromegrass (HBG) at Melfort and Saskatoon, Saskatchewan during a baseline 30 yr time period (1961-1990) and projected by three climate change scenarios (CGCM2 A21, CSIROMk2 B11 and HadCM3 A21) for three 30 yr time periods.

		Melfort				**Saskatoon**			
		Baseline	**CGCM2**	**CSIRO**	**HadCM3**	**Baseline**	**CGCM2**	**CSIRO**	**HadCM3**
		# of days supplement was required							
CWG	Baseline (1961-1990)	9 (0-150)				134 (0-183)			
	2020s		15.5 (0-80)	7 (0-106)	7 (0-65)		38 (0-142)	140 (0-184)	104 (0-180
	2050s		41 (0-165)	24 (0-98)	25 (0-178)		58 (0-164)	139 (0-185)	115 (0-174)
	2080s		44 (0-168)	44 (0-134)	66 (0-161)		66 (0-179)	157 (0-181)	121 (0-179)
HBG	Baseline (1961-1990)	0				77 (0-184)			
	2020s		0	0	0		0	42 (0-183)	42 (0-144)
	2050s		0	0	0		16 (0-171)	42 (0-135)	42 (0-182)
	2080s		0	1 (0-27)	0		6 (0-118)	53 (0-182)	53 (0-169)

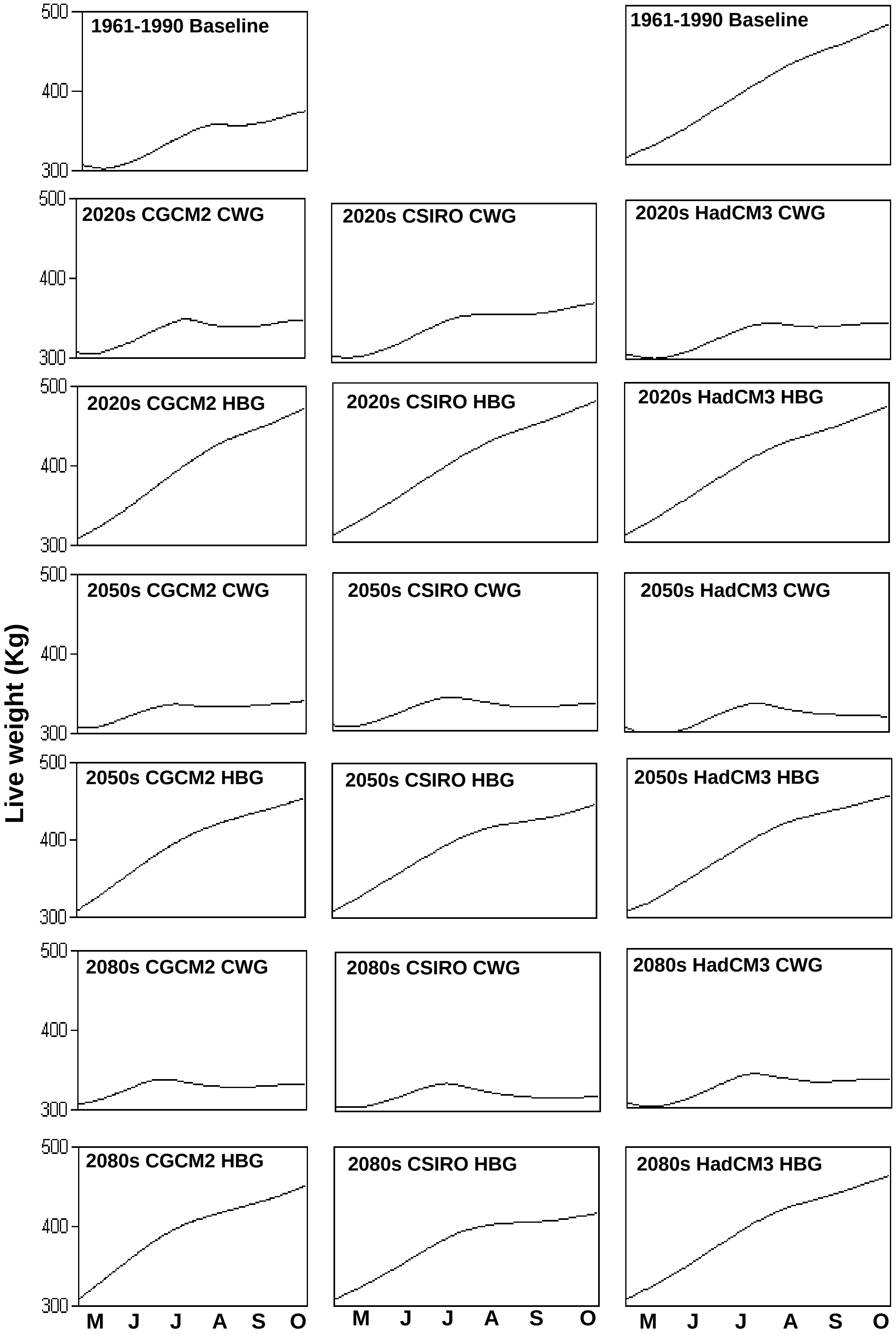


Figure 5.1 Simulated liveweights (kg) of steers grazing crested wheatgrass (CWG) and hybrid bromegrass (HBG) at Melfort 1961-1990 (Baseline) and during three future time periods 2020s, 2050s and 2080s from April 15-October 31 using three climate change scenarios (CGCM2 A21, CSIROMk2 B11 and HadCM3 A21).

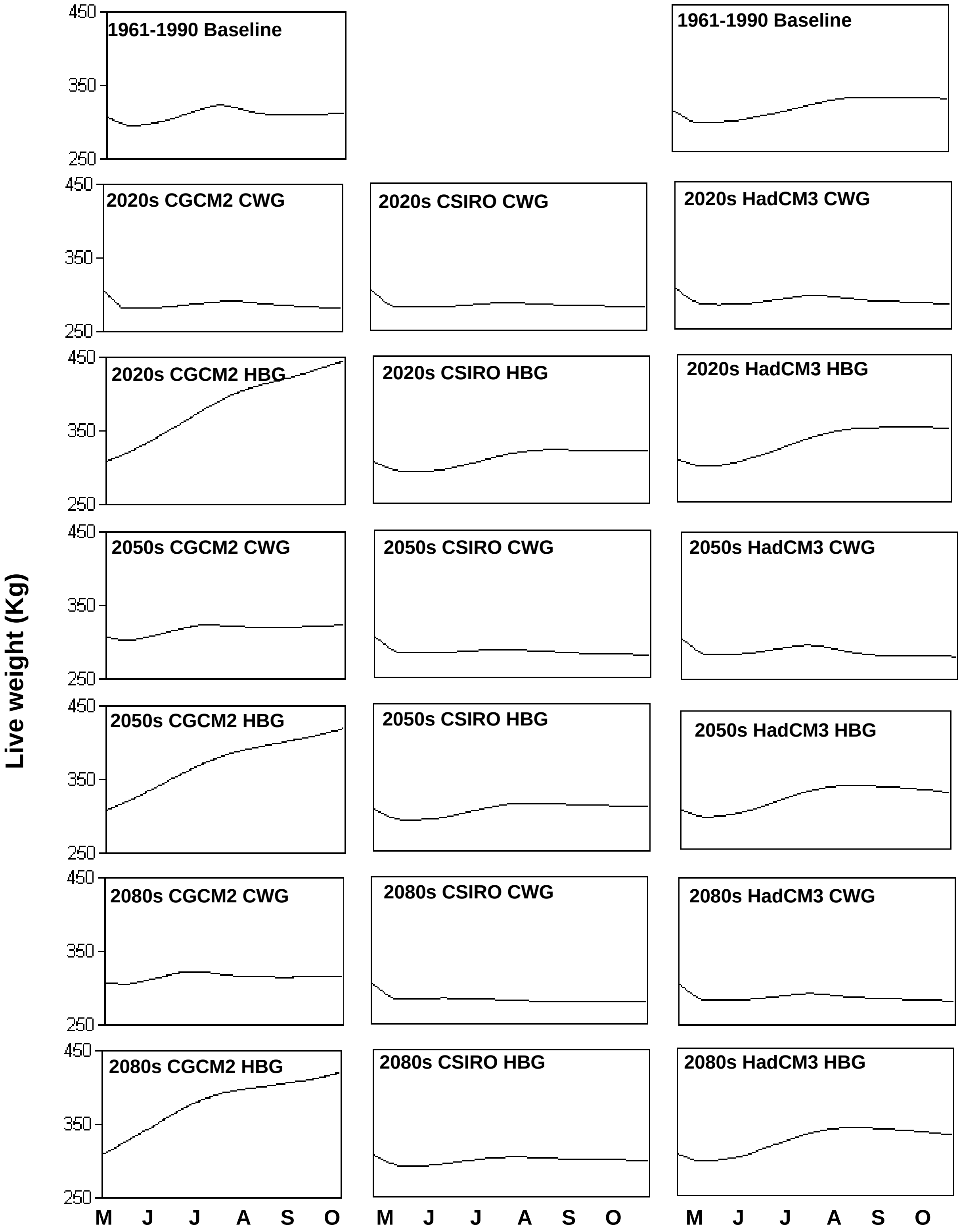


Figure 5.2 Simulated liveweights (kg) of steers grazing crested wheatgrass (CWG) and hybrid bromegrass (HBG) at Saskaton 1961-1990 (Baseline) and during three future time periods 2020s, 2050s and 2080s from April 15-October 31 using three climate change scenarios (CGCM2 A21, CSIROMk2 B11 and HadCM3 A21).

5.4 Conclusions

The results presented here suggest that the productivity of livestock at Melfort will continue to exceed that at Saskatoon and that hybrid bromegrass will continue to be superior to crested wheatgrass as a pasture grass. In addition, the results projected from the CGCM2 A21 scenario are more favorable to livestock production than those projected by CSIROMk2 B11 and HadCM3 A21 at both locations.

CHAPTER 6

6.0 SIMULATED EFFECT OF CLIMATE CHANGE ON BOTANICAL COMPOSITION OF MIXED SPECIES NATIVE PASTURE.

6.1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) has suggested that grasslands in North America may experience shifts in species composition (IPCC, 2001b). It is generally thought that the range of species will extend towards the pole as the climate warms. Plains rough fescue (*Festuca hallii*) is a circumboreal species (Gleason and Cronquist, 1991; Harms, 1985). Fescue grasslands are a transition zone between forests and mixed grasslands and plains rough fescue is a climax species in a number of non-forested and forested communities throughout its range. It is found in the fescue grasslands from eastern British Columbia to Manitoba and south to Colorado and North Dakota (Harms, 1985; Pavlick and Looman, 1984). Rough fescue occurs most prominently in a belt along the northern edge of the Great Plains where it is the principal climax dominant within the black-soil zone of Alberta, western Saskatchewan, and northwestern Montana (Coupland and Johnson, 1965; Pylypec, 1986). The distribution in western Canada ranges from 100º 35’ W to 120 45’ W, and from 49 º N to 54 º 20’ N, often in disjunct pockets (Figure 6.1). The reasoning for the disjunct pockets is unknown (Looman, 1969). The climate associated with Fescue grasslands can range from 40^{o}C in summer to less than -40^{o}C in winter (Looman, 1969). Precipitation on average is 400 mm and usually 50% falls between May and August (Looman, 1969). One important feature of fescue grassland climate is that these communities are found where the winter snow-cover is prevalent and drying winds are less common.

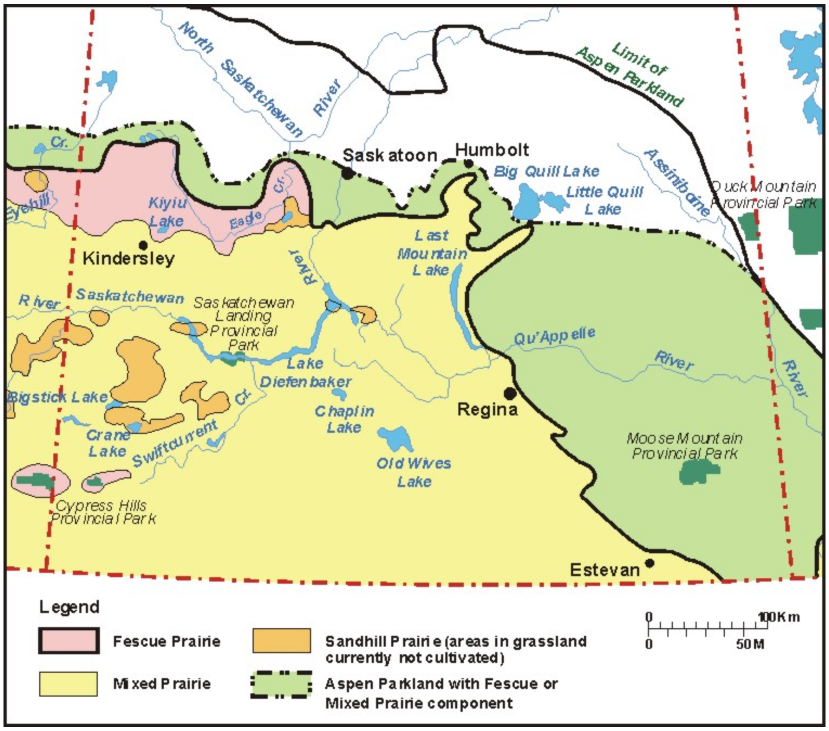


Figure 6.1 Distribution of Plains rough fescue in Saskatchewan indicated in pink and green (Coupland and Brayshaw, 1953).

Northern Wheatgrass (*Elymus lanceolatus* (Scribn. & Smith Gould) is another species that can be found in a fescue community. This cool-season C3, drought tolerant grass is the most common of all the native wheatgrasses in the Canadian Mixed Prairies (Maxwell and Redmann, 1978; Redmann, 1976; and Pyle and Johnson, 1990). Northern wheatgrass requires a minimum of 200-380 mm of annual precipitation (Redmann, 1978; Kowalenko and Romo, 1998). Western Wheatgrass (*Pascopyrum smithii* (Rydb.) A. Love) is also common in the mixed grass prairie, foothills fescue, parkland regions and northern Great Plains (Looman, 1983). The well-developed surface root system grows to 20 cm and deep roots to 150 cm, enabling this species to survive, produce during dry periods and to recover rapidly after prolonged periods of drought. In comparison to northern wheatgrass, western requires more annual precipitation (360-870 mm) (Sharp

Bros. Co., 1997) and reaches a 95% net primary production (NPP) at a lower temperature (21 ^{o}C) than northern wheatgrass (28 ^{o}C) (Meyers, 1999).

Green needle grass (*Nassella viridula* (Trin.)) is also a component of a fescue community (Johnston and Bezeau, 1962) and is a moderately drought tolerant species requiring average precipitation between 327-337 mm and temperature between 3.4 ^{o}C and 47 ^{o}C (Kowalenko and Romo, 1998).

Any temperature and moisture shifts could have a major effect on the species composition within the community. The effect of climate change on species shift in fescue grasslands has not previously been studied. The fescue species component of this cool-season native grass community provides important forage throughout its range. Plants are very productive and highly palatable to both livestock and wildlife. Therefore, studying the affects of climate change on this grassland ecosystem is important to both livestock and wildlife.

Major ecosystem shifts are expected in Saskatchewan (Sauchyn, 2007) and will be most visible at the margins of the grassland and forest. In this study, three potential climate change scenarios at two sites (Saskatoon and Melfort) were used to simulate potential changes in a four species mix of rough fescue, western wheatgrass, northern wheatgrass, and green needle grass pasture during three 30-yr future time periods.

6.2 Methodology

6.2.1 Decision Support Tool, Locations and Climate Scenarios

The Canadian version of GrassGro (Cohen et al., 2003; Cohen et al., 2004a; Perillat et al., 2004; Lynch et al., 2005) was the Decision Support Tool (DST) used for all simulations. Full details on this DST have been reported in Chapter 3. Two locations

Melfort 52 º 49’N 104 º 36’ W, elevation 480 m and Saskatoon 52 º 10’N 106 º 41’ W, elevation 501 m were chosen to represent the temperature and precipitation regimes of the fescue grassland region. Details of the baseline climate data (1961-1990) and the three climate change models used (CGCM2 A21, CSIROMk2 B11 and HadCM3 A21) have been previously reported in Chapter 4.

Simulations used recorded climate data sets from both locations for the time period 1961-1990 (baseline) and climate data generated from three climate scenarios for the 2020s (2010-2039), 2050s (2040-2069), and 2080s time period (2070-2099) as described in previous chapters to predict mean availability of herbage by species and the factors limiting growth.

6.2.2 Pastures and Soils

Four species were included in the simulated mixed native pasture. These were rough fescue, northern wheatgrass, western wheatgrass and green needle grass. This sward was chosen because these species are commonly found together. Meyers (1999) parameterized northern and western wheatgrasses and green needle grass and German (1999) parameterized rough fescue for GrassGro.

A sandy-loam topsoil / sandy-clay-loam subsoil (SL/SCL) soil texture association was assumed at both locations. The topsoil depth was assumed to be 280 mm and subsoil depth was assumed to be 1220 mm. A programmed removal of the standing crop every year on November 30 was included to allow effective use of light and moisture for new growth which would be impeded by the large build up of dead herbage and litter if it was not removed.

6.3 Results and Discussion

During the baseline years (1961-1990), simulated total biomass at both Melfort (Figure 6.2) and Saskatoon (Figure 6.3) was dominated by plains rough fescue, though the fescue was less dominant at Saskatoon. This is in agreement with the observations of Coupland (1992). During the three future 30-year periods (2020s, 2050s and 2080s) there was a gradual shift in species composition (Figures 6.2 and 6.3) resulting in complete dominance of northern wheatgrass at both locations by 2070.

There was little difference in the rate of species change between the three climate change scenarios at either location except that the change in species composition was less pronounced at Melfort with CSIROMk2 B11 than the other two scenarios during the 2020s, especially between 2010 and 2029. This shift at both locations was associated with the increase in summer temperatures reported previously in Chapter 2, which became the major limitation to growth of the fescue at both locations but had little effect on the growth of northern wheatgrass (Figures 6.4 and 6.5). This led to the eventual complete replacement of the fescue with northern wheatgrass that resulted in a significant decline in both green and total herbage production ($P<0.05$) at both locations with all climate change scenarios during all three future time periods (Table 6.1). There were, however, no significant differences between climate scenarios for green or total herbage production.

Figures 6.4 and 6.5 present the growth limits at both locations for simulations using only CGCM2 A21. However, the same trends were simulated using both CSIROMk2 B11 and HadCM3 A21, except that the temperature limitation with

CSIROMk2 B11 was less severe than CGCM2 A21 and HadCM3 A21 during the 2020s (Figure 6.6) and this resulted in the different rate of species shift with CSIROMk2 B11 at Melfort (Figure 6.2).

The simulations during the 2050s show clearly the sensitivity of plains rough fescue to temperature. Growth was close to zero by July as represented by the amount of available green herbage capable of intercepting light for photosynthesis. In contrast, northern wheatgrass was much less limited by the increase in summer temperature and was able to compete more effectively for the available soil moisture (Figures 6.4 and 6.5).

Table 6.1 The simulated mean (±SD) production of green and total herbage biomass of a mixed native pasture at Melfort and Saskatoon, Saskatchewan during 1961-1990 (baseline) and during 2010-2039 (2020s), 2040-2069 (2050s) and 2070-2099 (2080s) using three climate change scenarios (CGCM2 A21, CSIROMk2 B11 and HadCM3 A21). Difference within columns between baseline and climate change scenarios are indicated by *.

Location & Soil texture	Source	2020s		2050s		2080s	
		Green	Total	Green	Total	Green	Total
		Available Herbage (kg/ha)					
Melfort SL/SCL	Baseline	1017.1±547.0	3267.8±768.2	1017.1±547.0	3267.8±768.2	1017.1±547.0	3267.8±768.2
	CGCM2	603.9±291.2*	2484.8±481.5*	588.8±356.4*	2522.2±866.7*	572.1±350.2*	2719.8±897.6*
	CSIRO	739.7±445.2*	2827.0±800.5*	486.8±268.3*	2491.5±776.6*	403.7±294.2*	2399.2±942.6*
	HadCM3	690.6±342.8*	2576.6±609.8*	480.7±190.0*	2225.3±498.4*	557.2±204.8*	2646.1±665.1*
Difference + or - from baseline	CGCM2	413.2	783	428.3	745.6	445	548
	CSIRO	277.4	440.8	530.3	776.3	613.4	868.6
	HadCM3	326.5	691.2	536.4	1042.5	459.9	621.7
Saskatoon SL/SCL	Baseline	619.1±462.8	2432.8±746.1	619.1±462.8	2432.8±746.1	619.1±462.8	2432.8±746.1
	CGCM2	348.8±187.1*	1974.3±514.0*	397.6±297.7*	2004.7±820.9*	313.1±249.1*	1847.5±783.7*
	CSIRO	138.4±166.8*	1148.3±463.1*	112.8±107.4*	1068.0±461.1*	76.0±90.7*	1007.1±466.1*
	HadCM3	203.7±146.8*	1436.6±508.5*	179.9±126.0*	1338.0±440.6*	193.1±129.8*	1421.7±784.9*
Difference + or - from baseline	CGCM2	270.3	458.5	221.5	428.1	306	585.3
	CSIRO	480.66	1284.5	506.3	1364.8	543.1	1425.7
	HadCM3	415.4	996.2	439.2	1094.8	426	1011.1

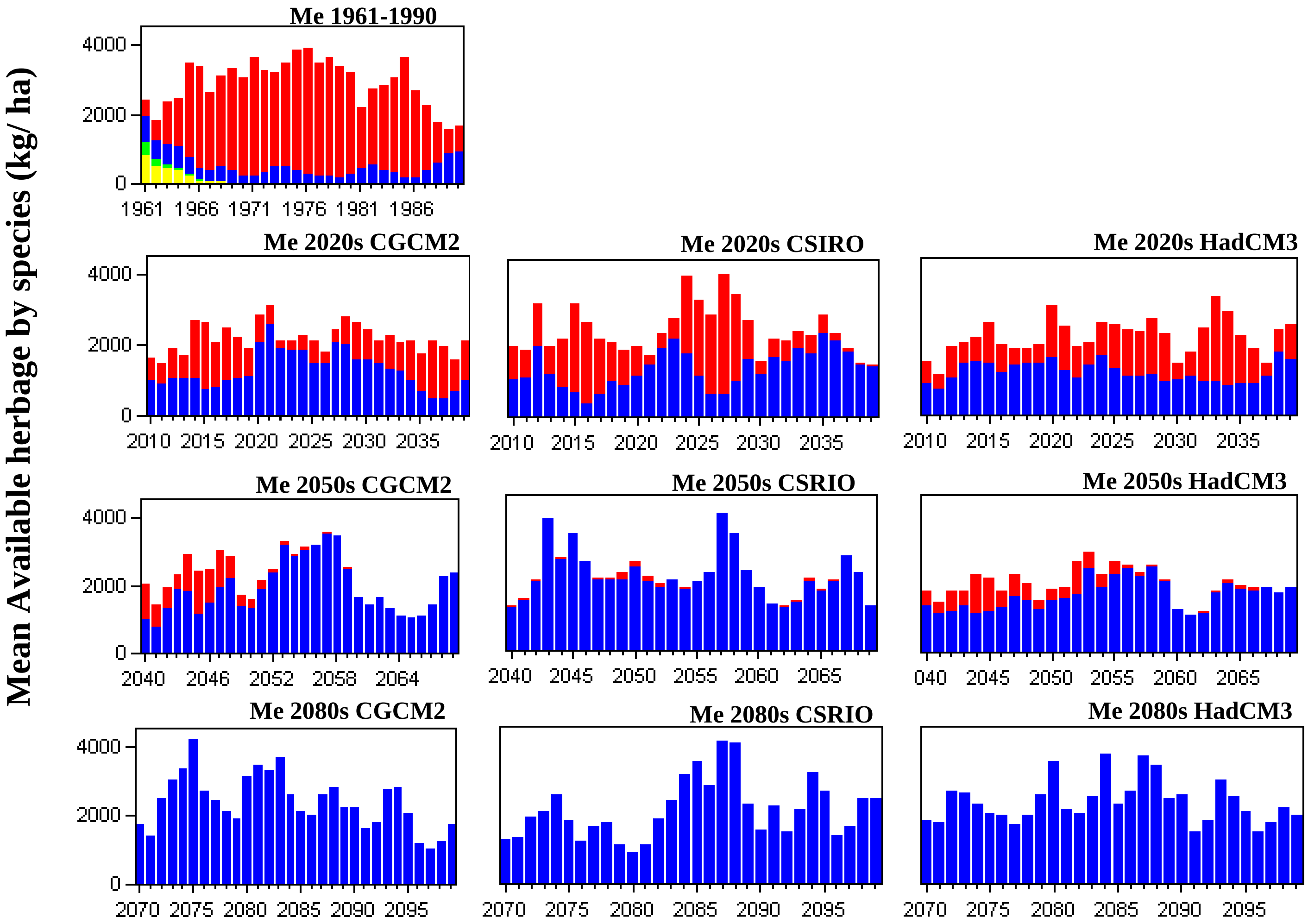


Figure 6.2 Simulated available herbage for Rough fescue (red), Northern wheatgrass (blue), Western wheatgrass (green), and Green needle grass (yellow) Melfort (Me). Top to bottom: baseline (1961-1990), simulations using three climate change scenarios, CGCM2 A21, CSIROMk2 B11 and HadCM3 A21 for 2020s (2010-2039), 2050s (2040-2069) and 2080s (2070-2099).

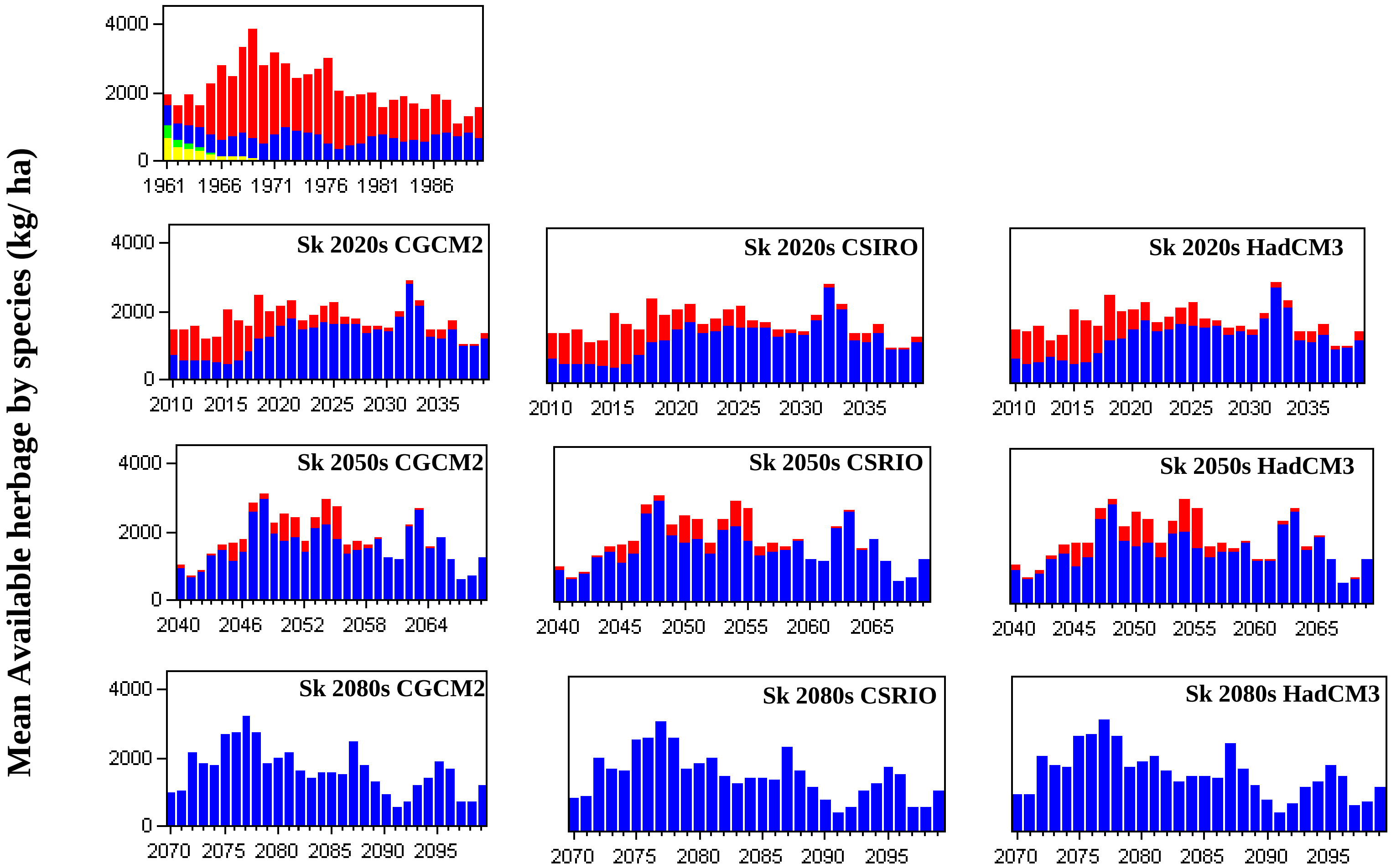
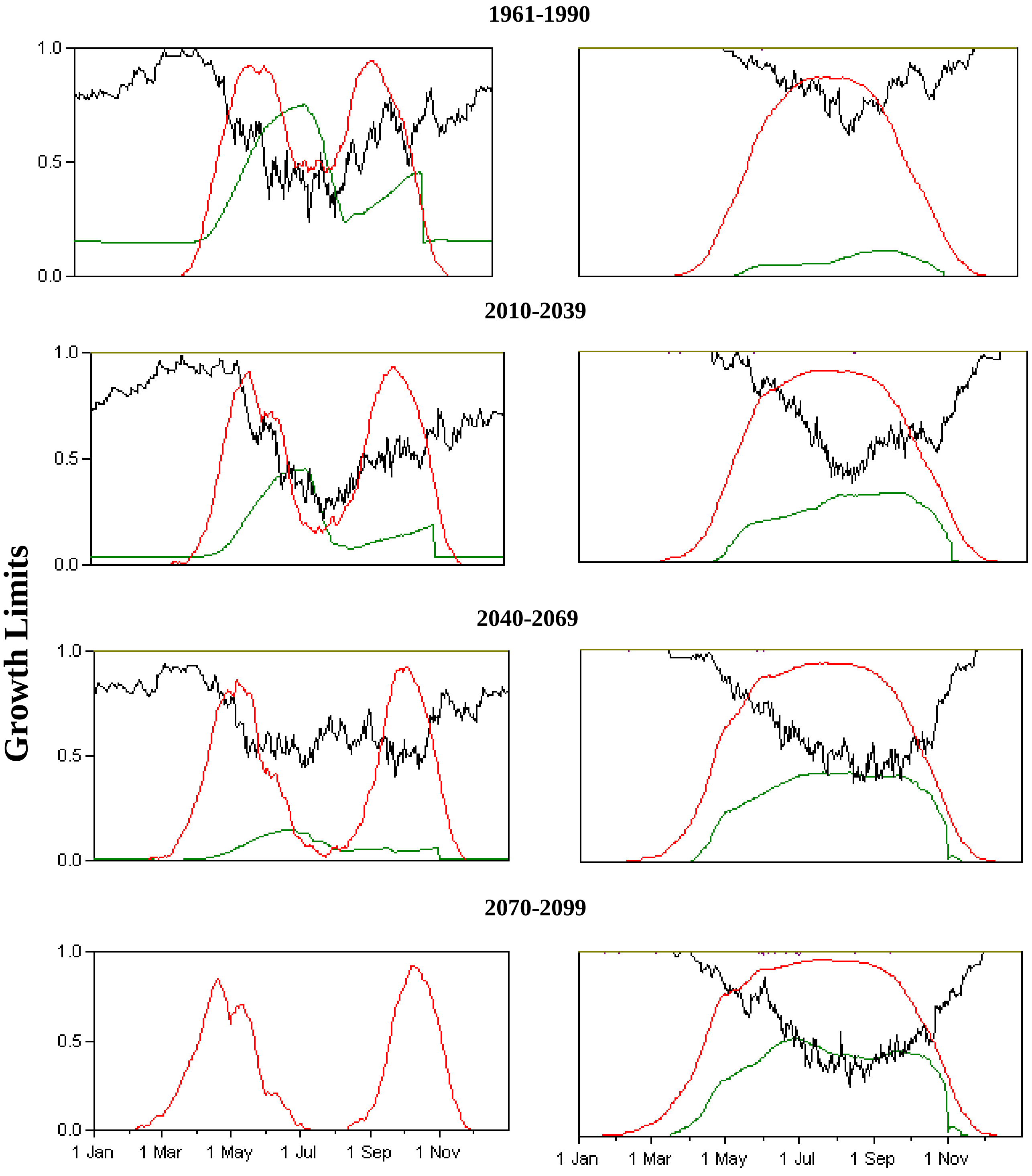


Figure 6.3 Simulated available herbage for rough fescue (red), northern wheatgrass (blue), western wheatgrass (green), and green needle grass (yellow) Saskatoon (SK). Top to bottom: baseline (1961-1990), simulations using three climate change scenarios, CGCM2 A21, CSIROMk2 B11 and HadCM3 A21 for 2020s (2010-2039), 2050s (2040-2069) and 2080s (2070-2099).



1961-1990

2010-2039

2040-2069

2070-2099

Figure 6.4 Simulated limitations to growth of rough fescue (left), and northern wheatgrass (right) - light interception by green herbage (green), temperature (red) and water (black) on a daily time scale for Melfort averaged over 30-yr time periods for baseline (1961-1990) and using CGCM2 A21 for the 2020s (2010-2039), 2050s (2040-2069), and 2080s (2070-2099). Scale 0 represents total restriction and 1 represents no restriction.

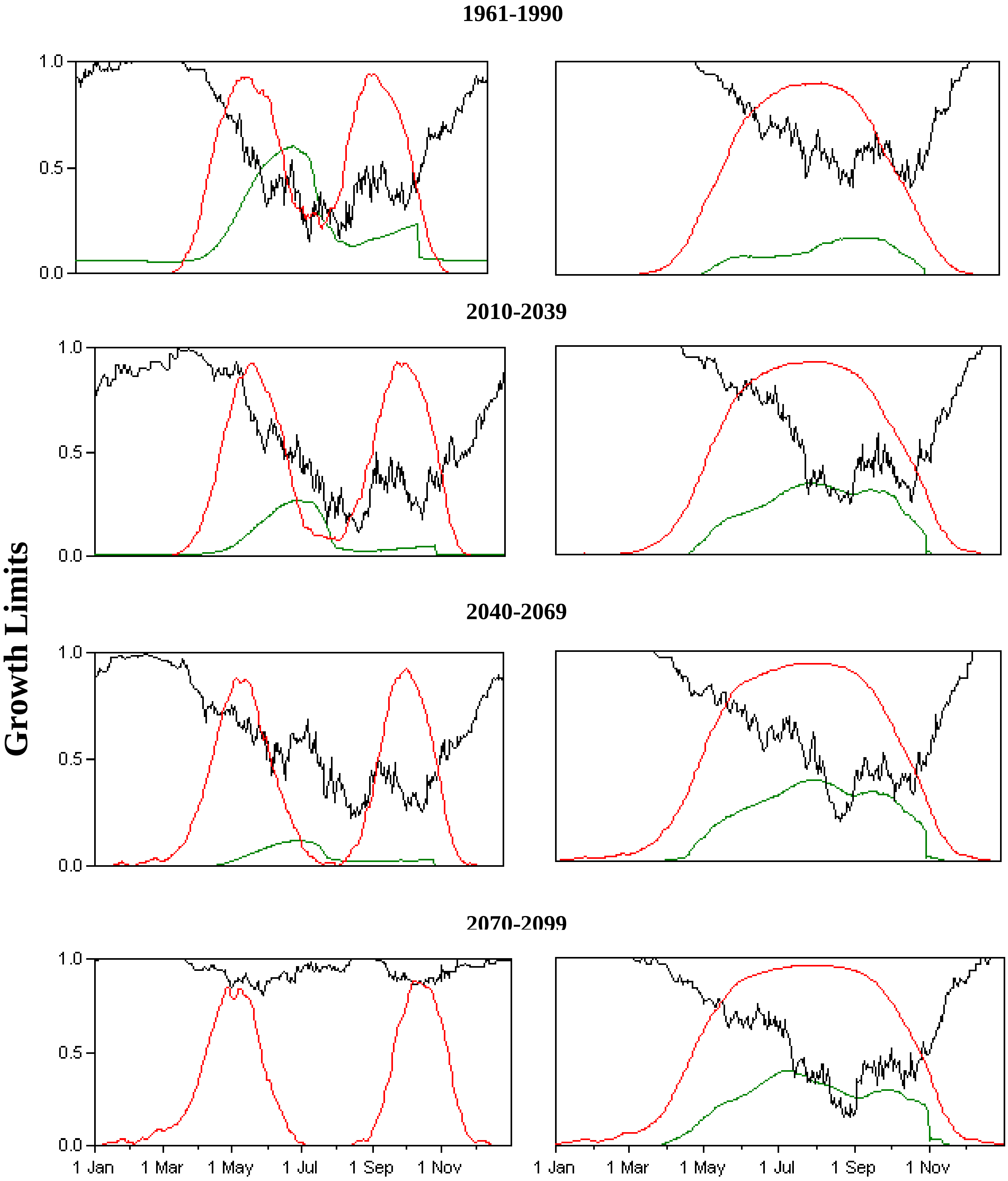


Figure 6.5 Simulated limitations to growth of rough fescue (left), and northern wheatgrass (right) - light interception by green herbage (green), temperature (red) and water (black) on a daily time scale for Saskatoon averaged over 30-yr time periods for baseline (1961-1990) and using CGCM2 A21 for the 2020s (2010-2039), 2050s (2040-2069), and 2080s (2070-2099). Scale 0 represents total restriction and 1 represents no restriction.

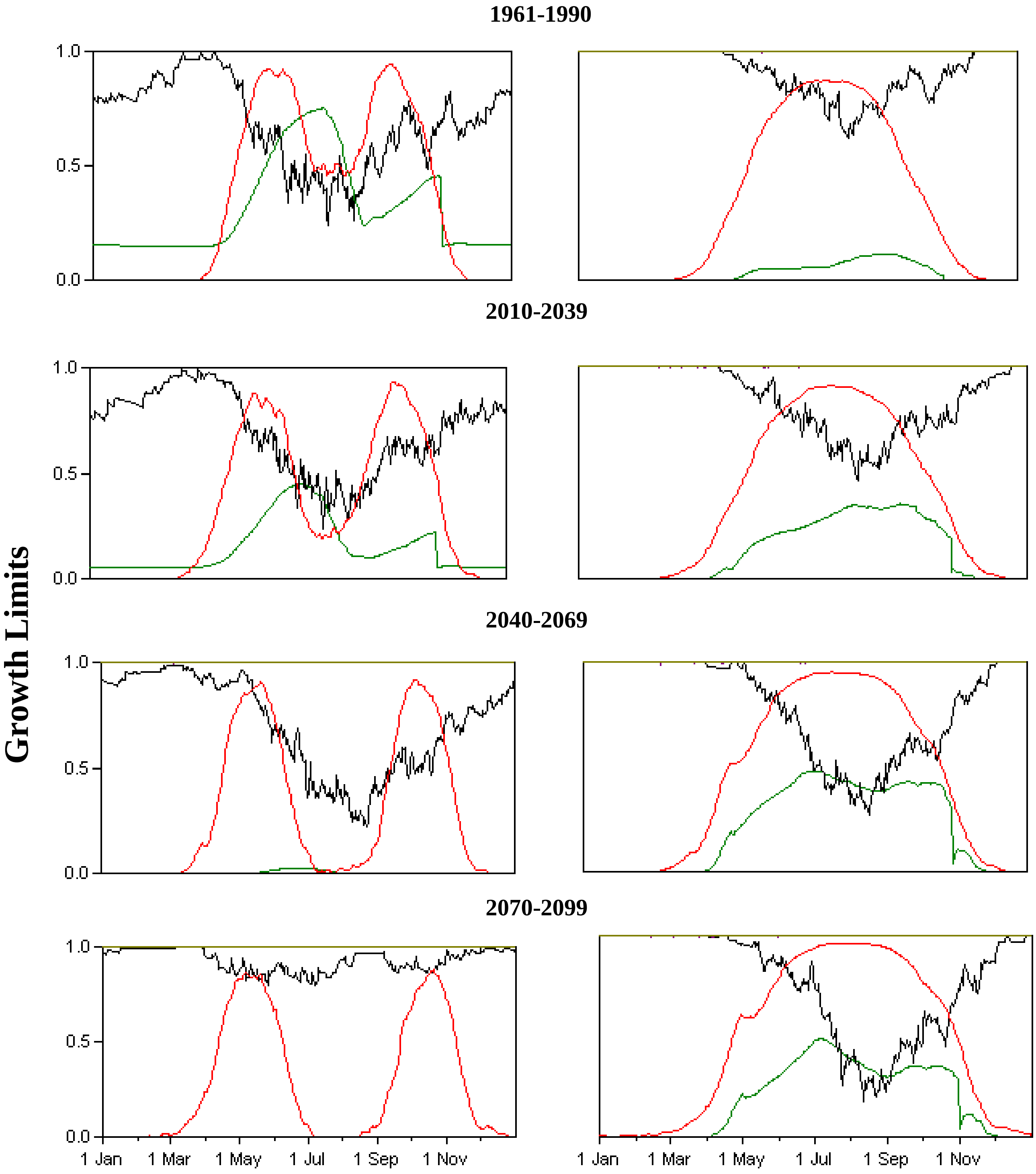


Figure 6.6 Simulated limitations to growth of rough fescue (left), and northern wheatgrass (right) - light interception by green herbage (green), temperature (red) and water (black) on a daily time scale for Melfort averaged over 30-yr time periods for baseline (1961-1990) and using CSIROMk2 B11 for the 2020s (2010-2039), 2050s (2040-2069), and 2080s (2070-2099). Scale 0 represents total restriction and 1 represents.

6.4 Conclusions

The complex interactions between factors such as temperature, moisture and species in a mixed grassland requires a multifunctional approach in order to predict and understand the effects of climate change on the ecology of grasslands.

The potential ecological consequences of climatic change in grassland regions have not been studied extensively and are thus subjected to much speculation (Coffin and Lauenroth, 1996). The simulations presented here have attempted to focus attention on the ecological consequences of climate change. However, further simulations are required using other species, locations and GCMs to determine the likely effects of climate change on other mixed grassland associations.

CHAPTER 7

7.0 GENERAL DISCUSSION AND CONCLUSIONS

On the Canadian Prairies, soil moisture is a major limiting factor for plant growth. Soil moisture is also closely associated with climate (precipitation, temperature, solar radiation, wind), plant cover, plant growth and soil texture and these factors cannot be considered in isolation but must be integrated into a single decision support tool with a daily time step such as GrassGro to be of real value in predicting the effects of climate change on agricultural production. This study used MetAccess and GrassGro to incorporate future climate scenarios on a daily time-step, make projections of future seasonal changes in minimum and maximum temperature, precipitation and evaporation and to predict soil moisture. Further studies used these projections to evaluate the effects of climate change on the productivity and nutritive quality of two tame forage grasses and the intakes and production of grazing steers and to predict a shift in a multi-specific native *Festuca hallii* dominant grassland to a mono-specific *Elymus lanceolatus* grassland.

The research indicated the importance of evaluating the effects of climate change on a seasonal rather than an annual basis. However, there is a high degree of uncertainty accompanying projections of greenhouse-induced climate change and it is not possible to predict the future with accuracy; nor is it possible to confirm the accuracy of the predictions. There is a high degree of variability in the data between years, as indicated by the large standard deviations of the means, and in some cases the standard deviation was even larger than the mean. Moreover, this was true for each of the three climate change scenarios studied. For example, within the CGCM2

A21 climate model at Melfort alone, the projected annual average maximum temperatures ranged from 6.3 °C in 2015 to 17.2 °C in 2097 and the projected annual average minimum temperatures ranged from –6.5 °C in 2014 to 5.3 °C in 2097. These compared with a recorded range in annual maximum and minimum temperatures of 4.4 °C in 1972 to 9.2 °C in 1987 and -6.8 °C in 1972 to -2.0 °C in 1987, respectively. Similarly, projected average total precipitation ranged from 234 mm in 2091 to 963 mm in 2082 in comparison to a low of 334 mm in 1990 and a high of 653 mm in 1973. These results support the common consensus that the future climate will be warmer on average but more variable than during 1961 – 1990.

In comparison, the range in predictions of herbage yield, which were similar to those predicted by Thorpe et al. (2004), and liveweight gain of steers did not vary from baseline as greatly, suggesting that grass and livestock will have some resilience to the effects of climate change. For example, using the same climate scenario (CGCM2 A21), the predicted total herbage yield of hybrid bromegrass at Melfort ranged from a low of 1129 kg ha $^{-1}$ in 2060 to a high of 4348 kg ha $^{-1}$ in 2045 compared with a range during the baseline years from 849 kg ha $^{-1}$ in 1961 to 4539 kg ha $^{-1}$ in 1974. The average daily gains of steers grazing this pasture, using the same management guidelines as those used in Chapter 5, ranged from a low of 0.09 kg d $^{-1}$ in 2065 to a high of 1.0 kg d $^{-1}$ in 2047 compared with 0.03 kg d $^{-1}$ in 1961 to 1.1 kg d $^{-1}$ in 1974.

There has been limited research on herbage yield and grazing of hybrid bromegrass. Therefore, comparisons between field research and simulated baseline data presented in this thesis are difficult. Thompson (2003) reported one study that evaluated hybrid bromegrass using grazing steers during two years at Lanigan, Saskatchewan. However, due to the differences in grazing periods, stocking rates, turnout dates, grazing methods and management comparisons between that field study and the present simulation results valid comparisons cannot be made. For similar reasons, it is not possible to compare the results of the simulations with crested wheatgrass during the baseline years presented here with those reported by Thompson (2003) or Cohen et al. (2004b) at Lanigan, Saskatchewan.

It is important to emphasize that the simulated results for steers grazing the tame grasses are presented for only a single stocking rate and single grazing period (April 15 – October 31) chosen to be close to optimal for one of the grasses (hybrid bromegrass) at one location (Melfort). It is entirely unrealistic to expect that Saskatoon, with a lower annual rainfall, could support the same stocking rate and grazing period as Melfort. It is entirely likely that choosing a different stocking rate and different dates for the start and/or end of the grazing season would improve the overall productivity of the crested wheatgrass and the grazing steers at both Saskatoon and Melfort. However, while these choices may improve the average daily gain of the steers, the improvement would come at the expense of a lower carrying capacity and/or reduced length of the grazing season. Therefore, the results clearly indicate that the productivity of grazing livestock should continue to be greater at Melfort than Saskatoon and that hybrid bromegrass will be better adapted to climate change than crested wheatgrass at both locations.

There is an almost infinite number of management practices that can be used for adapting to climate change such as varying the stocking rate, varying the grass species, using various grazing management strategies such as rotation or complementary grazing systems, varying the dates and length of the grazing period, varying the supplementary feeding practices, varying the use of fertilizer and so on. A decision support tool such as GrassGro can be used to simulate the likely response to any number of these management possibilities. In addition, the further regional downscaling of climate predictions and the development and refinement of parameter sets for other pasture species will increase the scope and precision of predictions of the effects of climate change on pastoral production and the subsequent development of adaptation strategies.

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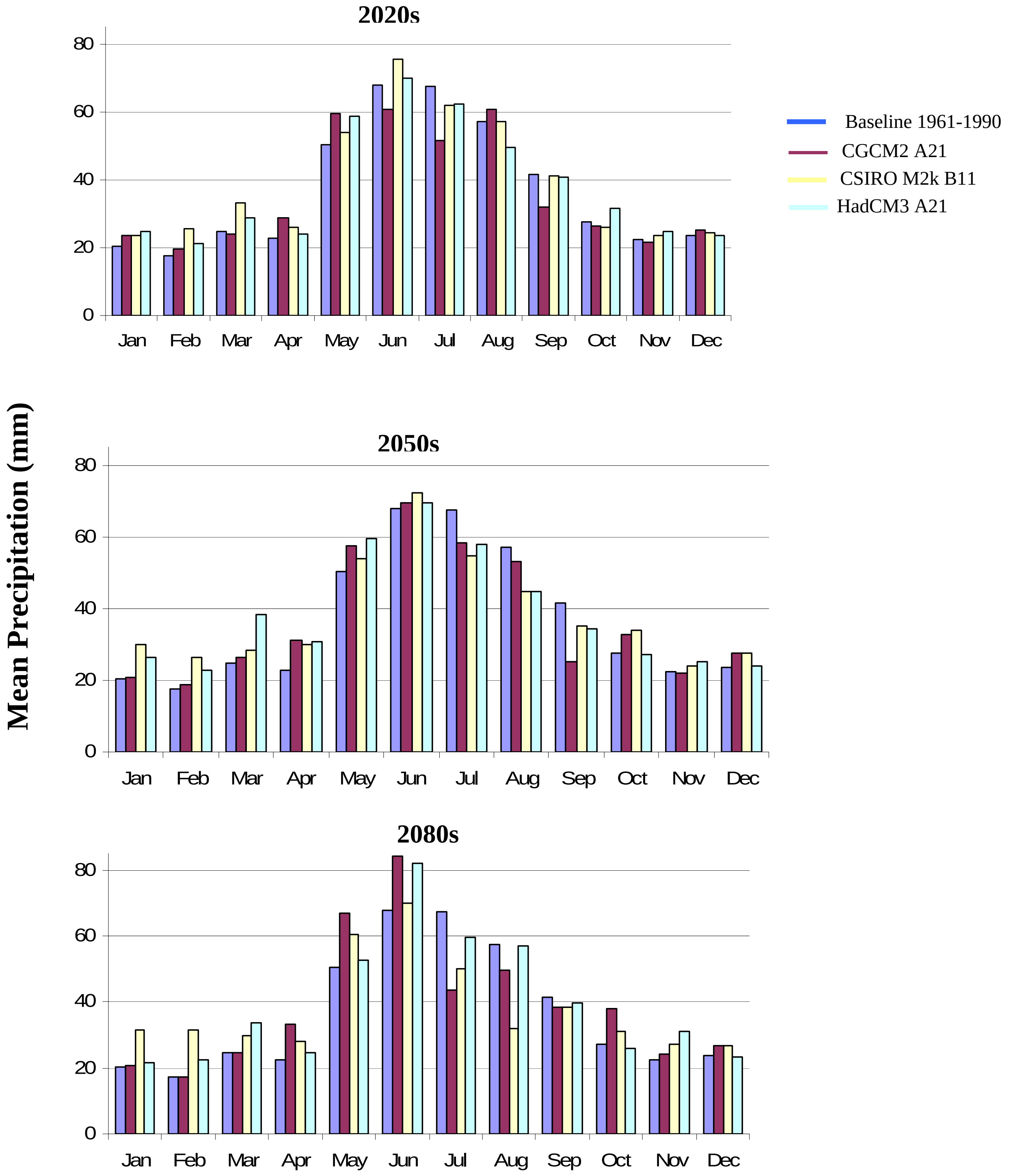
APPENDIX A

Mean annual precipitation for 1961-1990 (baseline) and during three climate scenarios (CGCM2 A21, CSIROMk2 B11 and HadCM3 A21) for the 2020s, 2050s and 2080s at Saskatoon.



2020s

2050s

2080s

APPENDIX B

Mean annual precipitation for 1961-1990 (baseline) and during three climate scenarios (CGCM2 A21, CSIROMk2 B11 and HadCM3 A21) for the 2020s, 2050s and 2080s at Melfort.