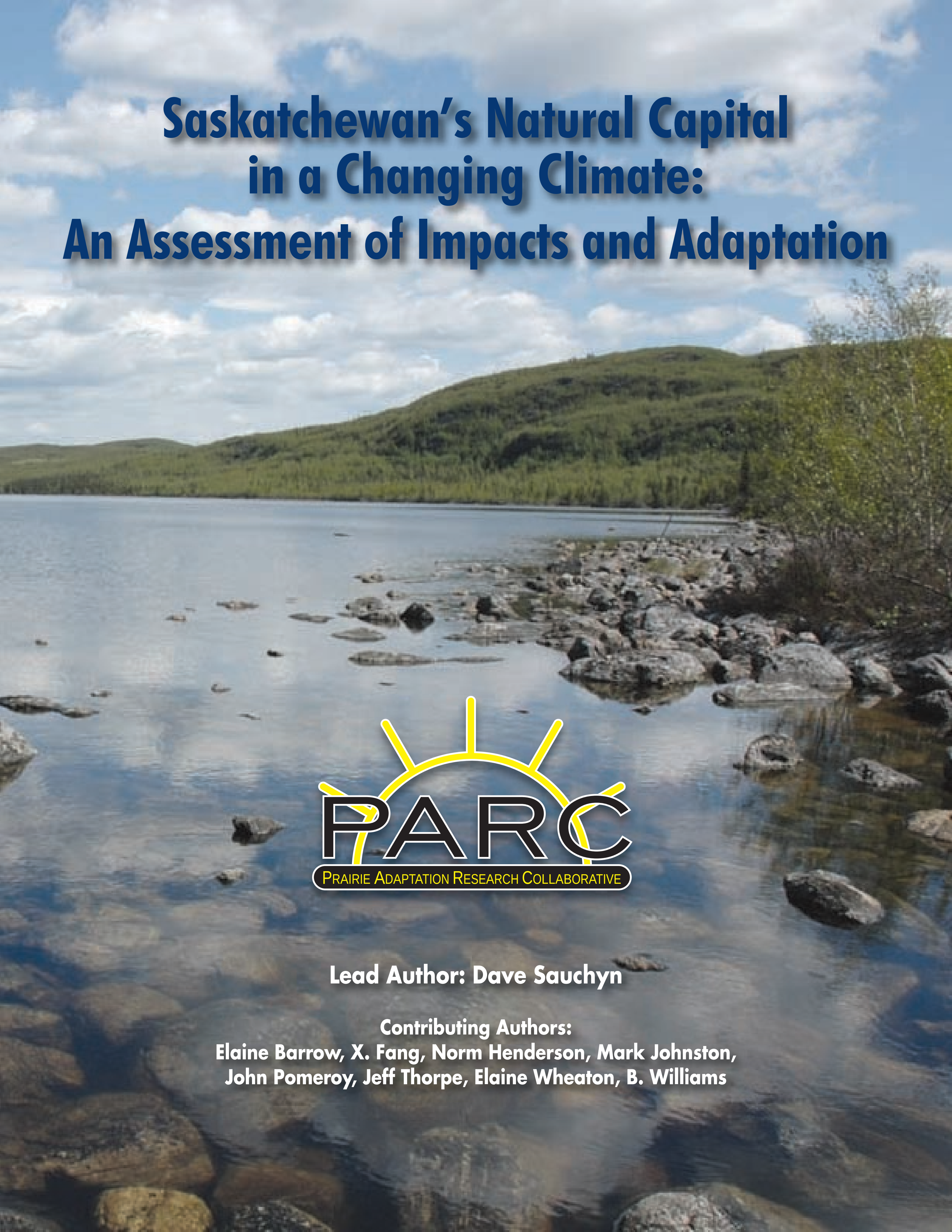
Saskatchewan's Natural Capital in a Changing Climate: An Assessment of Impacts and Adaptation



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EXECUTIVE SUMMARY

Climate change impacts in Saskatchewan are already evident, and will become increasing significant over time. This report draws on the expertise of top climate change researchers and a large body of previous work to create a state-of-knowledge synthesis of key biophysical impacts and adaptation options specific to Saskatchewan. The focus is Saskatchewan's ecosystems and water resources and the sectors of our economy, agriculture and forestry, which are most dependent on these natural resources. The purpose of this assessment report is to 1) document the expected impacts of climate change on Saskatchewan's natural resources and dependent industries, and 2) outline options for adaptation of resource management practices, policies and infrastructure to minimize the risks associated with the impacts of climate change and to take advantage of opportunities provided by a warming climate.

Saskatchewan has one of the world's most variable climates. There is a high degree of variability between seasons, years and decades. There is also a large difference in mean temperature and precipitation between the southwest and northeast corners of the province. Thus throughout this report we make the distinction between the grassland and forest regions of the province, in terms of climate scenarios, impacts and adaptation. Recent trends in annual and seasonal temperature strongly suggest that Saskatchewan is not getting hotter, but rather ''less cold.'' In particular, there has been a greater increase in daily minimum (as opposed to maximum) temperatures and the largest warming has occurred during winter and early spring, resulting in a longer frost-free period and more growing degree days. Historical trends in the summer climate moisture index (CMI = precipitation – potential evapotranspiration) suggest a significant decreasing trends of between 1 and 4 mm/yr in southern Saskatchewan. Reconstructions of the climate of the past several millennia reveal multi-centennial shifts in moisture regimes and droughts that are more severe and prolonged in the centuries before Saskatchewan was settled by EuroCanadians. This longer-term view of the climate indicates that the climate that we have experienced in Saskatchewan over the past half century, while variable, did not encompass the range of conditions captured by records of the recent pre-instrumental past or the range of conditions projected for the near future under global warming.

The Canadian Prairies have warmed at a faster rate than the global average and our future climate will be outside the range of natural variability. For the purpose of this assessment of climate change impacts and adaptation, a new set of climate scenarios has been developed for Saskatchewan. Across a range of global climate models and greenhouse gas emission scenarios, there is a consistent increase in mean annual temperature and precipitation throughout Saskatchewan. These are more favourable climatic conditions for most activities, and especially agriculture, depending very much, however, on the distribution or timing of the extra heat and water. Most of the warming is occurring in winter, such that the frost-free growing season is getting longer, although we are also losing some of the advantages of a cold winter that excludes many pests and diseases, and stores water as snow, the most abundant, reliable and predictable source of water. Most of the extra precipitation is expected in winter and spring and increasingly in the form of rain as the climate warms. Scenarios summer precipitation are less consistent but include decreased summer precipitation falling in fewer and more intense storms. Thus on average, the mid to later stages of the longer warmer summers will tend be drier, possibly much drier. While a shift to warmer wetter winters and drier summers is almost certain, most of the risk from climate change will be an increase in the year to year variability, and the climate scenarios that project drought, and unusually wet years, with greater severity and frequency than in the past.

Prairie province hydrology is dominated by cold regions processes so that snowmelt is the primary hydrological event of the year for both the major rivers that derive from the Rocky Mountains and small streams and rivers that arise in Saskatchewan. Climate change impacts on water resources are therefore focused on changes to snow accumulation, snowmelt and infiltration to frozen soils. Climate change scenarios suggest generally warmer and wetter winters for Saskatchewan. Large scale hydrological models that take these scenarios into account suggest changes in the annual streamflow of the South Saskatchewan River ranging from an 8% increase to a 22% decrease, with an 8.5% decrease being an average prediction. Small scale hydrological models for prairie streams suggest a 24% increase in spring runoff by 2050 followed by a 37% decrease by 2080 as the winter snowcover becomes discontinuous. Both model results suggest that there is not a dramatic drying of the prairies to be anticipated under climate change and that in some cases streamflow will increase for certain scenarios and under moderate degrees of climate change. While prairie runoff should increase in the near term, as climate change progresses later in the 21st C there will be dramatic drops in runoff and the flow of small streams to wetlands and depressions and to small prairie rivers.

For the major rivers draining from Alberta into Saskatchewan, more efficient water use for irrigation or a reduction in irrigated acreage in Alberta could compensate for the reduced water availability, which is due mainly to reduced mountain snowmelt. Current minimum tillage and continuous cropping systems are resilient for most climate changes to agricultural water resources. Infrastructure will have difficulty keeping up with this level of change unless agricultural land management is used to compensate for changes in hydrology. New crop varieties and tillage methods which are able to leave some water for runoff to natural ecosystems will need to be devised. Drainage of wetlands may have to be reversed to limit high spring streamflows and wetland/lake levels.

Integrated basin management of the South Saskatchewan River across both Alberta and Saskatchewan and for smaller watersheds in Saskatchewan is the preferred adaptation method for dealing with these uncertainties. Integrated basin management plans with apportionment powers, enforceable land use controls and agricultural management incentives will need to be implemented to deal with rapid changes and increased uncertainties in water management designs.

In all cases the uncertainties in the model outputs and driving hydrometeorological data for current simulations make recommending adaptation measures very difficult as the range of predictions is from a decrease to an increase in available streamflow compared to current estimates. It is imperative that the scientific basis of these hydrological models be improved so that there is reduced uncertainty in model predictions. The current climate and water resources available in the headwater basins are themselves uncertain and need to be better quantified to permit more reliable comparisons of future climate and water resource predictions with the current situation.

Saskatchewan faces major climate change impacts on ecosystems and landscapes that will combine and interact with impacts of land use activities. Changes in climate will alter environmental conditions to the benefit of some species, and detriment of others, often with economic consequences. The key climate change impacts on forest ecosystems are an increased rate and intensity of forest disturbances, such as fire and pathogens, and the possible loss of forest cover in grassland-forest ecotone regions, that is, the southern boreal forest and the island forests of the Prairie Ecozone. A potential increase in plant productivity with a longer and warmer growing season and increasing atmospheric CO_2 may be limited or overwhelmed at many sites by moisture limitations or other constraints. New landscape ecosystems might evolve; for example, a drier climate in southern Saskatchewan could potentially support shortgrass prairie currently found farther south. The increased stress on aquatic ecosystems from warmer and drier conditions, and loss of wetlands, could place prairie aquatic species at risk of extirpation and cause declines in migratory waterfowl populations.

We have many adaptation options, and some alternative choices about future ecosystems, but it will not be possible to maintain Saskatchewan's ecosystems as they were or as we know them now. The new climate-driven reality is that biodiversity managers need to think of themselves not as practitioners of preservation, but as "creation ecologists", since antecedent landscapes can no longer be effectively targeted. We have options, but the past is not one of them. Passivity in the face of impacts may shrink our ecosystem options, particularly in Prairie forests. However, active management entails some risk and expense. Whatever options we choose, the future ecosystems that result from climate change in Saskatchewan will be unprecedented.

Soil is a major element of Saskatchewan's natural capital and historically the basis for the regional agricultural economy. The climate scenarios outlined above, with longer drier summers occurring more often, could cause Saskatchewan's soil landscapes to respond with local instability and erosion. This could include erosion and shallow slope failure caused by less frequent but more intense rainfall; more widespread wind erosion, sand dune activity and dust storms, with impacts on health, tourism, transportation and agriculture; a risk of desertification over a larger area as the extent of semiarid to subhumid climate expands beyond southwestern Saskatchewan; and soil moisture thresholds below which landscapes are more vulnerable to disturbance and potentially desertified.

Land degradation is preventable throughout the subhumid Prairie Ecozone under current climatic conditions, policy framework and crop and soil management regimes. With better soil, water and crop management, the production of cereal crops has become less vulnerable to climate variability, although not to sustained drought. Within the last 20 years, different cropping systems and the adoption of soil conservation practices, specifically reduced tillage and zero-till, have begun to reverse the decline in soil productivity across the prairies crop land. Soil conservation practices can be defeated, however, by extreme climatic events and especially by consecutive years with droughts. Institutional adaptive responses to the soil degradation crisis of the 1980s-90s have reduced sensitivity of soil landscapes to climate over a large area. Other institutional mechanisms are required to provide rewards and incentives for adaptive soil and crop management practices that reduce vulnerability to climate change.

Climate impacts on the agricultural sector and adaptive responses are already occurring and these are likely to accelerate in the future. Changes in many agro-climatic variables, including growing season length, accumulated heat units, and precipitation are fairly well documented and recognized. Climate variability is a main determinant of crop yield. Future climate change impacts on crop production are still uncertain, but consistent with recent changes and tending to converge towards increasing trends in the near-term until certain thresholds of climate change are reached. This upward trend is then followed by average decreases and interrupted by large losses accompanying severe climatic events, such as droughts and excessive moisture. The complex interactions of the effects of insects, diseases, and weeds on agricultural production are still not understood well enough to offer substantial findings for projected impacts. The loss of cold winter is contributing to the increasing risk of some pests, reduced water (snow) storage, and other problems. Conflicts over increasingly scarce water supplies are one of the most serious risks for agriculture and society. Projections of temperature increases are more certain than the slight annual precipitation increases, and the resulting higher evaporative demand is a strong driver of summer surface water deficits. Although warming winters are generally favorable for livestock production and management, increasing threats of stresses related to heat, water, insects and diseases, and other climate hazards tend to offset gains. Extreme weather and climate are “wild cards”. A trend of increasing frequency and severity of extreme events is fairly certain, but the detrimental effects are not considered well or at all in future estimates of agricultural production.

Growth in agricultural productivity would require the best adaptation measures to deal with climate change and other compounding effects. Adaptation needs to be proactive, effective, innovative, and strategic and in some cases, places, and times, substantive, including changes to management and policy regimes. Enhanced adaptation would be beneficial now. Policies and institutions are currently constrained in their adaptive capacities to deal with climate change by weak networks with science and ability to use climate information. Agriculture is also expected to play a role in mitigating greenhouse gas emissions and storing carbon, amid many other challenges, including markets, and energy and food security issues. Appropriate integration of both adaptation and mitigation in agriculture is needed to ensure that they are coordinated and mutually supportive. Climate change information must be mainstreamed into strategic, operational, and policy considerations. Beneficial farm management practices, with adaptive components, may be useful in dealing with adaptation deficits. Best management practices that enable coping with droughts and climate change include water well management, land management for soils at risk, cover crops, nutrient recovery from waste water, irrigation, enhancing biodiversity, grazing plans, and integrated pest management planning.

Saskatchewan’s forests are already vulnerable to range of natural disturbance and climate-related factors. Fires, insects and drought have had major impacts on the forest and will continue to do so regardless of climate change. Warmer, drier conditions in the future, and interaction of factors, will likely magnify the impacts. In particular, the southern margin of the boreal forest will become increasingly vulnerable to a range of climate change impacts and may eventually loose forest cover all together. On the positive side, there may be some locations where other conditions are not limiting and CO_2 fertilization may result in increased productivity.

The adaptive capacity of the forest management community in Saskatchewan is high in terms of the ability to implement sustainable forest management. However, there is less capacity in term of the scientific details of climate change impacts, and increasing the interactions between scientists and managers should be a priority. The concept of "embedded science" can be an effective approach to educating both managers and scientists about implementing adaptation. Considering climate change in forest management will require further information on impacts at a scale consistent with decision-making. Forest management institutions need to be examined for the extent to which they support or hinder the development and implementation of adaptation options. Consideration of new species, assisted migration of existing species and populations, and revised tenure agreements are examples of policy changes that could assist in more effective adaptation. Local autonomy and flexibility in decision-making will become increasingly important in an environment in which conditions are changing rapidly and where the past is no longer a guide to the future.

INTRODUCTION

Climate change impacts in Saskatchewan are already evident, and will become increasing significant over time. Building on previous major work, in particular the global-scale IPCC Fourth Assessment (IPCC 2007) and on the national-scale "From Impacts to Adaptation: Canada in a Changing Climate 2007" (Lemmen *et al*. 2008), this report draws on the expertise of top climate change researchers to create a state-of-knowledge synthesis of key biophysical impacts and adaptation options specific to Saskatchewan. The focus is Saskatchewan's ecosystems and water resources and the sectors of our economy, agriculture and forestry, which are most dependent on these natural resources.

The following section of this report is a brief overview of regional climate observations of the past several decades and how these recent trends appear when viewed from the perspective of long paleoclimate records and climate model simulations. For the purpose of our assessment biophysical impacts, Dr. Elaine Barrow developed a new set of "Climate Scenarios for Saskatchewan". Her companion report is summarized here and describes how Saskatchewan's climate is likely to evolve in response to continued greenhouse gas emissions. The other members of the assessment team have translated these projected climate changes into impacts and considered the adaptations required to mitigate future risk and realize new opportunities. However, since this report is primarily a review of current knowledge based on published research, the climate impact studies that we reviewed were based on prior scenarios of future climate, although they are generally similar to those summarized below and detailed in Dr. Barrow's report "Climate Scenarios for Saskatchewan". The major content of this assessment of Saskatchewan's natural capital in a changing climate is the description of the climate change impacts and adaptation options for Saskatchewan's water resources, ecosystems, soil landscapes, agricultural systems and forest industries. The report concludes with a synthesis of key findings and recommendations for the use of this information for strategic planning of adaptation to climate change in Saskatchewan.

PAST CLIMATE AND RECENT TRENDS

Saskatchewan's Baseline Climate

There are a number of observed baseline climatologies for Western Canada, including Saskatchewan. In all cases, observed station data have been used to create gridded fields of observed climate. The PRISM gridded climatology (Daly *et al*. 1994) was used by Barrow (2009) to represent 1961-1990 baseline conditions for the province. Some of her results are summarized here to provide a brief description of the baseline (1961-90) climate of Saskatchewan.

Figures 1-3 are provincial maps of mean annual temperature and annual and seasonal precipitation for 1961-1990. There is a general gradient of decreasing temperature from the southwest of the province to the northeast in all seasons. In winter, the coldest mean temperatures, less than -25°C, occur in the north-eastern corner of the province. Mean temperatures in the far southwest corner are between -5°C and -10°C. In summer most of the province to north of La Ronge has mean temperatures between 15°C and 20°C, while the remainder of the province including Stony Rapids is slightly cooler at 10°C to 15°C.

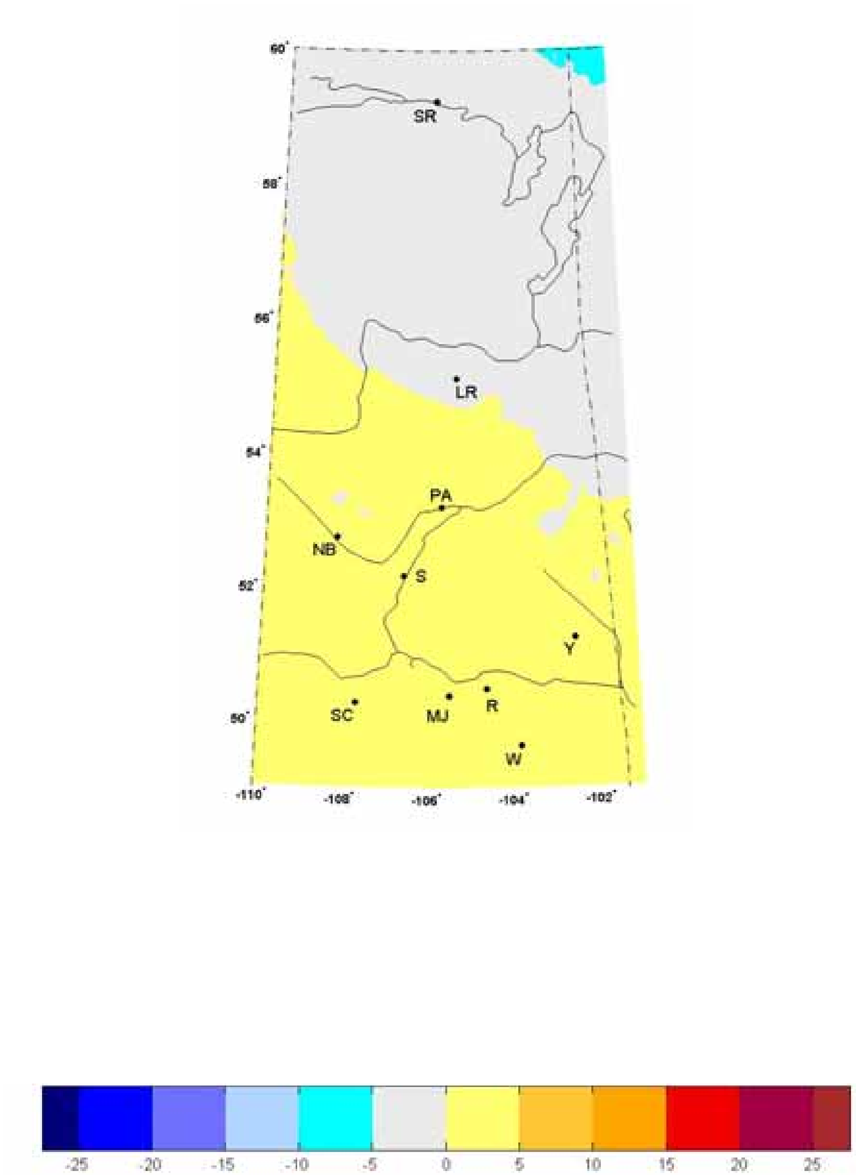


Figure 1: 1961-1990 annual mean temperature (°C) for Saskatchewan. SR – Stony Rapids; LR – La Ronge; PA – Prince Albert; NB – North Battleford; S – Saskatoon; Y – Yorkton; SC – Swift Current; MJ – Moose Jaw; R – Regina; W – Weyburn.

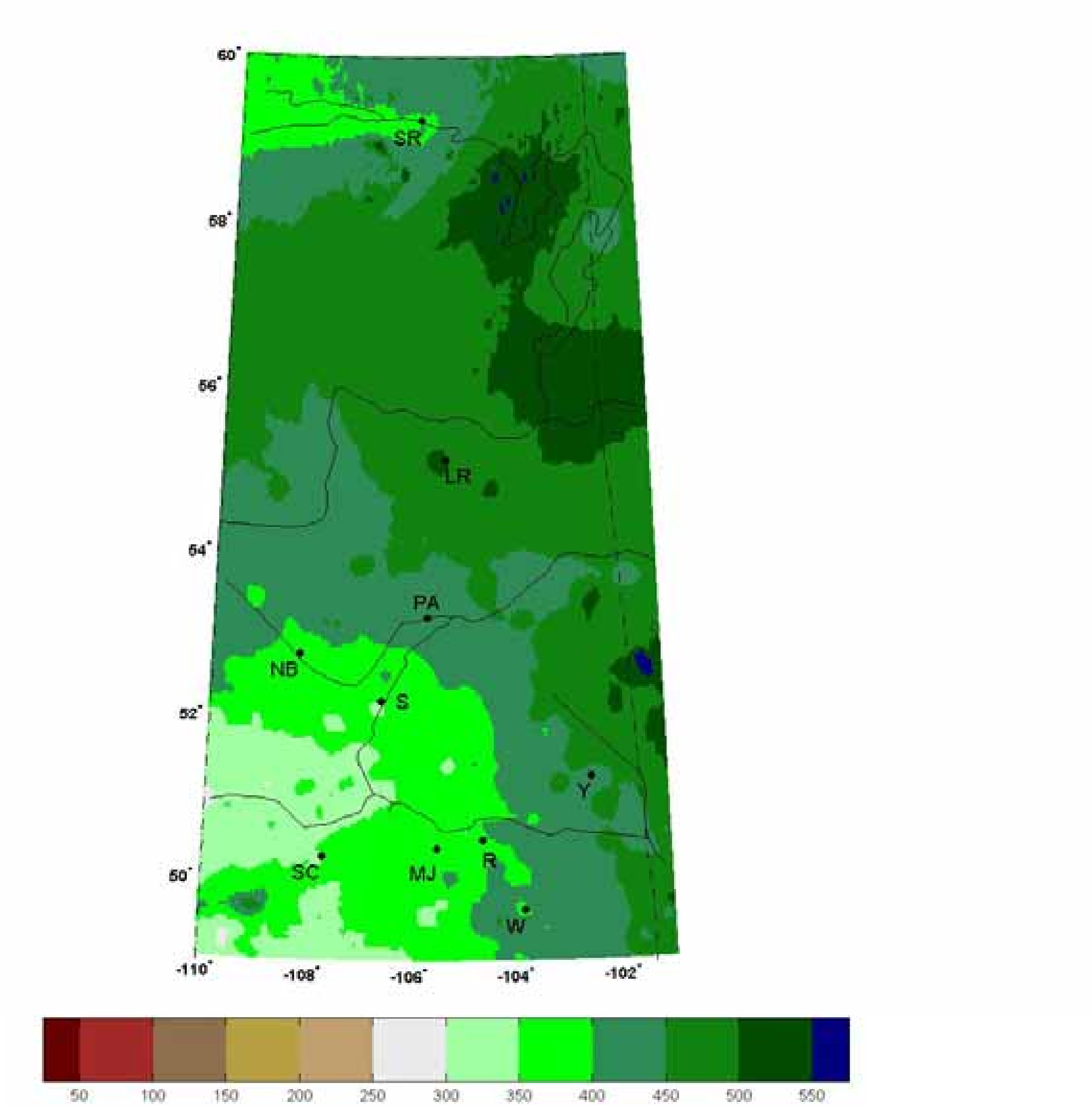


Figure 2: PRISM 1961-1990 annual precipitation totals (mm) for Saskatchewan. SR – Stony Rapids; LR – La Ronge; PA – Prince Albert; NB – North Battleford; S – Saskatoon; Y – Yorkton; SC – Swift Current; MJ – Moose Jaw; R – Regina; W – Weyburn.

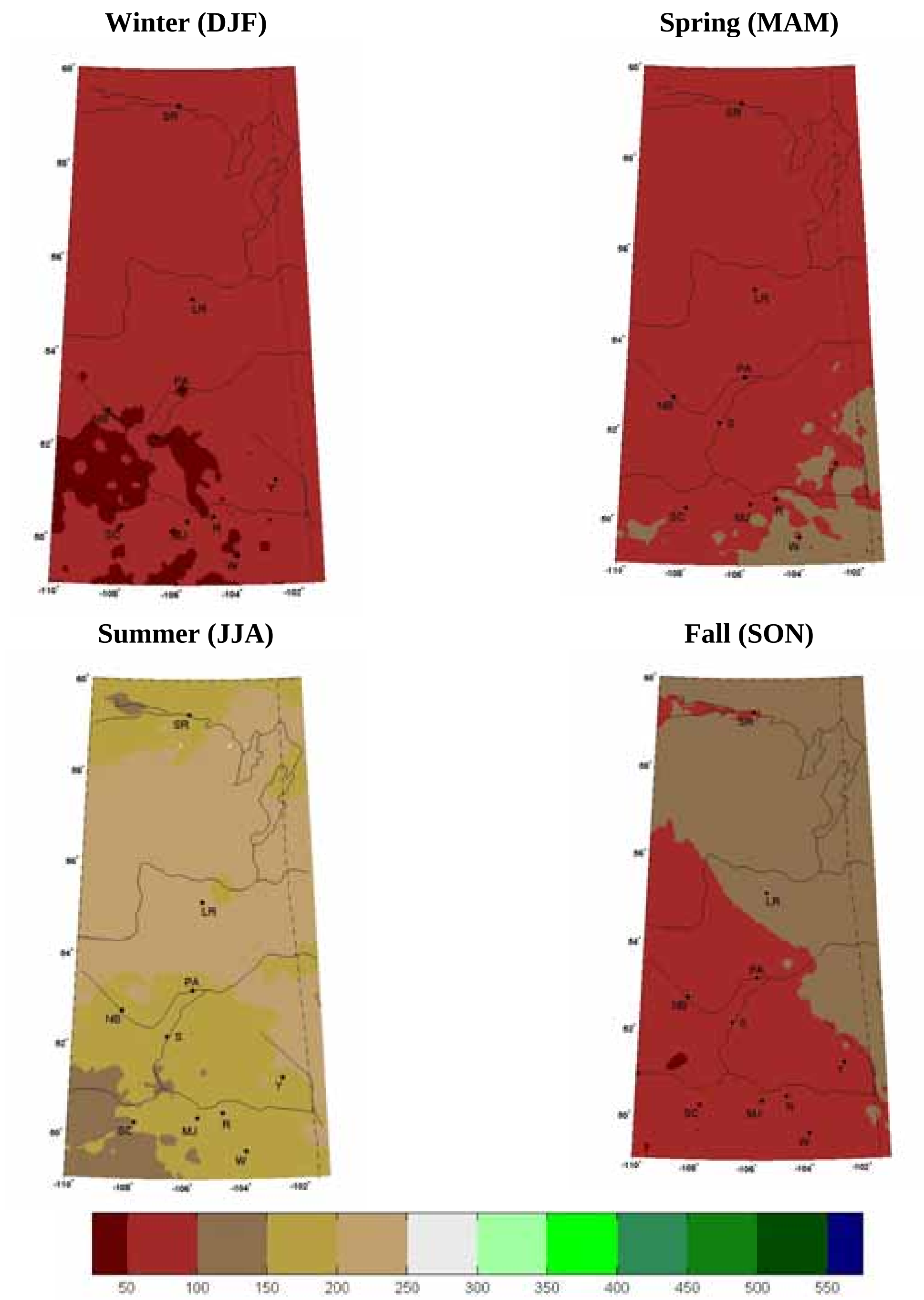


Figure 3: PRISM 1961-1990 seasonal precipitation totals (mm) for Saskatchewan. SR – Stony Rapids; LR – La Ronge; PA – Prince Albert; NB – North Battleford; S – Saskatoon; Y – Yorkton; SC – Swift Current; MJ – Moose Jaw; R – Regina; W – Weyburn.

The largest amount of precipitation is in summer. The southwest corner of the province receives least precipitation, on average, between 100 – 150 mm. Precipitation totals increase towards the northeast: between 150 and 200 mm up to and including Prince Albert, between 200 and 250 mm in a band including La Ronge and then a slightly drier region in the north-west of between 150 and 200 mm, including Stony Rapids. Winter and spring precipitation patterns are similar, with most of the province receiving between 50 and 100 mm. In spring, the south-east corner of the province is slightly wetter with totals between 100 and 150 mm. In fall, the southwest is slightly drier than the north-east, with precipitation totals between 50 and 100 mm compared to 100 to 150 mm, respectively.

Recent Climate Trends

The climate has warmed since Saskatchewan was settled and the first weather stations were established. Figure 4 illustrates that, while there is significant difference in mean annual temperature between Prince Alberta and Swift Current, temperature has increased consistently since 1895 at the locations and the three others plotted in Figure 4. The same trends apply to every weather station in Saskatchewan. Various studies (Beaubien and Freeland 2000, Zhang *et al.* 2001, Shabbar and Bonsal 2003, Bonsal *et al*. 2001, Zhang *et al*. 2000, Bonsal and Regier 2007) have examined climate trends in western Canada. There has been a decreased frequency, intensity and duration of cold spells. This trend would be expected in a warmer world. For the period 1950–1998, the greatest increase in daily maximum temperatures has occurred during the winter and spring season with no increase or decreases during the fall season. Mean daily maximum temperatures have warmed by more than 3.0°C during the last 49 years in some regions of western Canada in both winter and spring. Increases in daily minimum temperature have occurred in spring, winter and summer, although they are statistically significant only in spring. The number of frost days over most of Alberta and Saskatchewan have decreased with a few minimal increases scattered throughout the provinces. The frost free season is longer generally due to an early spring start and similar fall ending date.

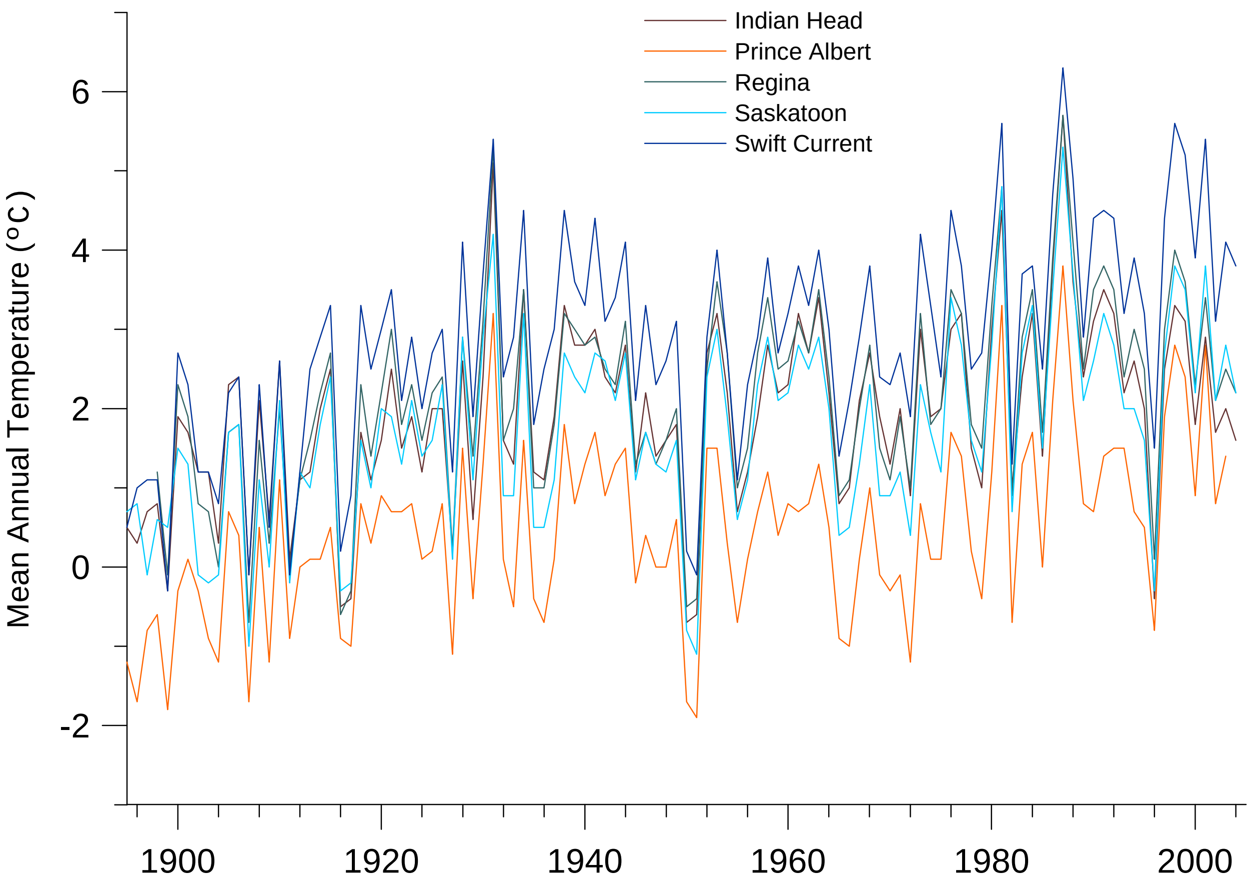


Figure 4. Mean annual temperature records for five Saskatchewan communities.

There are also trends toward more days with extreme high temperature in winter and spring, but these are not as pronounced as the decreases to extreme low values. There is no indication of any consistent changes to the magnitude of extreme high daily maximum temperature during summer, although substantial variability is observed between decades. These results from daily temperature analyses corroborate those of annual and seasonal temperature in that they strongly suggest that western Canada is not getting hotter, but rather ‘‘less cold.’’ In particular, there has been a greater increase in daily minimum (as opposed to maximum) temperatures and the largest warming has occurred during winter and early spring. Increases during summer have only been observed for minimum temperature. This observed warming has beneficial effects that include a longer frost-free period and more growing degree days. However, changes to the timing of temperature-related events (*e.g.*, spring runoff) could ultimately have adverse effects.

Total precipitation has increased over the last 99 years. Precipitation has a steady increasing trend from the 1920s to 1970. This precipitation trend appears to have stopped in about 1970 for the annual time series but not for seasonal time series. Areas in southern Saskatchewan during the fall season have decreasing trends. The ratio of solid to total precipitation has also increased annually over the prairies with the greatest increase occurring in fall, but there is a decreasing trend in central Saskatchewan. The southern part of the province, and some central areas, has experienced summer precipitation decreases.

Historical trends in the summer climate moisture index (CMI = precipitation – potential evapotranspiration) suggest a significant decreasing trends of between 1 and 4 mm/yr in southern Saskatchewan. This drying trend throughout the central and southern regions of the province is in contrast to increased CMI, *i.e.*, less dry conditions, along the Rocky Mountains the source of water for much of Saskatchewan's population. The most severe and prolonged Prairie-wide droughts during the instrumental record occurred in the early part of the 20th century (1915 through the 1930s), with severe individual drought years in 1961 and 1988. The spatial extent and severity of the 2001/2002 drought ranked below the early episodes, however, it was one of the top 10 worst droughts during the instrumental period. It followed a prolonged absence of dry years. 2001 and 2002 were the worst one year droughts since 1961, and the worst two-year drought since 1929–1930; 2002 was one of the worst one-year droughts on record.

Past Climate

Global climate changes are known from the study of geological and biological archives that preserve a measurable response to climate fluctuations. These proxy climate records define the range of natural climate variability and provide historical analogues of future climate. Long-term trends and large departures from mean climate conditions are apparent only in paleoclimatic records. Instrumental records are too short and are confined to the interval of time during which human activities have significantly increased the atmospheric concentrations of greenhouse gases. Recent climate, of the past few millennia, provides the best context for understanding present climate change. With the Medieval Warm Period (MWP) of the 9th to 14th centuries, and the Little Ice Age (LIA) of the 15th to 19th centuries, the global climate the past two centuries may have encompassed a large range of variation in temperature (Bradley 2003). Temperatures from boreholes in Canada's western interior (Majorowicz, *et al*. 2002) show the significant warming of the past few centuries. In Saskatchewan, variations in climate over the past several millennia are reflected in the migration of the boundary between grassland and forest, and fluctuations in the level and salinity of lakes (Williams *et al*. 2009).

Most of paleoclimatic records from Saskatchewan have been derived from the physical (*e.g.* level), chemical (*e.g.* salinity) and biological (*e.g.* biodiversity) characteristics of lake sediments. The frequency and duration of dry periods also has been inferred from the age and history of sand dune deposits (Wolfe 1997), which are extensive in southern Saskatchewan. The regional reactivation of a dune field would require a dry periods lasting several years to decades (Vance and Wolfe 1996).

These lake and sand dune records indicate early in the Holocene (the past 10,000 years) the climate of Saskatchewan was generally warmer and drier than today culminating in the mid-Holocene warm dry 'climatic optimum', when dune activity was so extensive that evidence was not preserved (Wolfe *et al.* 2002). The pollen records suggest aspen parkland where today there is coniferous forest (Sauchyn and Sauchyn 1991, Vetter *et al. 20*00). A post mid-Holocene shift to more humid conditions is indicated by increasing lake levels and elevated levels of spruce/ pine and aquatic plant pollen.

The lake records suggest that the last thousand years were relatively cool and humid, but there are indications of episodes of aridity: for example about 600 BP at Oro Lake, 700 BP at

Waldsea Lake, and 1100 to 900 BP and 600 to 300 BP at Redberry Lake. In the Great Sand Hills (Wolfe *et al. 20*01), a period of dune stability occurred around 2600 BP. Dune reactivation was dated at 600 and 300 BP and during the last 200 years. In the Elbow Sand Hills an episode of wind erosion within the last 220 years was caused by either drought or some sort of disturbance (*e.g.* fire) confined to this area.

Given the limits of the accuracy of determining the age of sediments, they usually provide coarse climate histories. The reconstruction of annual to decadal climatic variability requires more accurate dating methods, using archives such as tree-rings, that provide both proxy climate and chronological control. These methods and archives of higher resolution are applicable mainly to the past millennium. High-resolution lake sediment records have been obtained recently with the continuous sampling of sediment cores at fine intervals. The diatom assemblages from Humboldt Lakes revealed multi-centennial shifts in moisture regime (Laird *et al. 20*03, Michels *et al*. 2007). A marked shift to moister conditions at ca. 800 BP at Chauvin Lake and ca. 670 BP at Humboldt Lake occurs near the end of the Medieval Warm Period and the onset of the Little Ice Age.

From the precise optical dating of quartz grains, Wolfe *et al.*, (2001) identified widespread reactivations of sand dunes about 200 years ago and correlated this geomorphic activity with tree-ring records of prolonged droughts of the mid to late 18th century. A lag is apparent between peak dryness ca. 1800 and the onset of dune activity ca. 1810. Dune stabilization has occurred since AD 1890. The droughts of the 1930s and 1980s were insufficient to renew dune activity.

The only climate proxy with consistent and absolute annual and seasonal resolution is tree rings. In the dry climate of Saskatchewan, tree growth is limited each year by available soil moisture and therefore tree rings are a proxy of precipitation and drought. Using tree rings, Beriault and Sauchyn (2006) reconstructed stream flow in the Churchill River Basin as far back as 1840, considerably longer than the instrumental record, which begins in 1930. Periods of below average stream flow were identified in the mid and late19th century, as well as early in the 20th century. Prolonged periods of above average and then below average flow in the last half of the 20th century are unprecedented over the reconstruction period. Similarly, Vanstone and Sauchyn (2008) used tree rings from bur oak in the eastern Qu'Appelle River Valley to construct a record of drought and stream flow. Tree-ring chronologies from the Cypress Hills of southwestern Saskatchewan provided a signal of annual moisture conditions for the past three centuries (Sauchyn and Beaudoin 1998, Sauchyn *et al. 20*02, 2003, Sauchyn and Skinner 2001). They show prolonged droughts prior to Euro-Canadian settlement of the western plains. These long droughts affected sand dune activity, the fur trade and the health of aboriginal people. The tree rings and other climate proxies suggest that the climate of the 20th century was relatively favourable for the settlement of Saskatchewan, because the sustained droughts of preceding centuries did not occur. Data for the period 1961-1990 is used to define the world's 'normal' climate. According to paleoclimate records, this may have been the most benign climate of the past 750 years in the Canadian prairies (Sauchyn *et al. 20*02). This lack of severe or prolonged drought during the latter half of the 20th century is evident in a recent 600-year reconstruction of the flow of the South Saskatchewan River by Axelson and Sauchyn (In Press). This proxy water level record is plotted in Figure 5 as departures from the mean: positive (wet years) in blue and negative (dry years) in red. There are years and periods of low flow which are longer and/or more severe in the pre-settlement period.

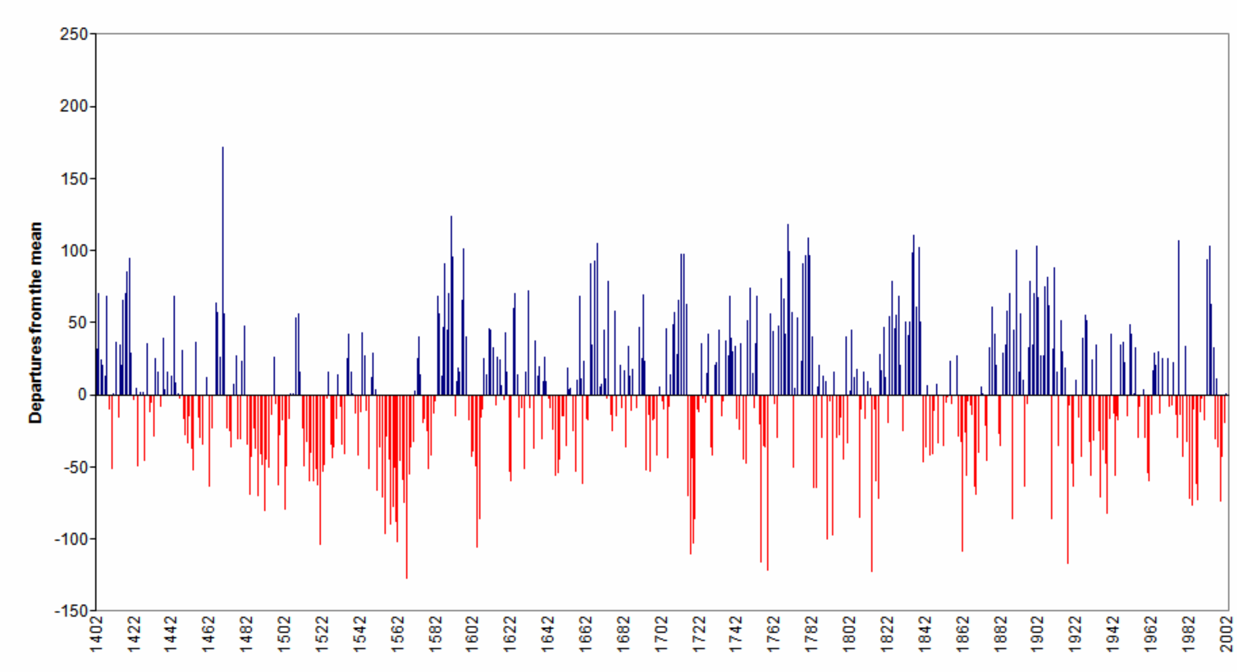


Figure 5. Reconstructed flow of the South Saskatchewan River, 1402-2004, plotted as departure from the mean annual flow (m^3/sec). Positive departures from the mean (wet years) are in blue and negative departures (dry years) are in red. (from Axelson and Sauchyn, In Press)

SCENARIOS OF THE FUTURE CLIMATE

Introduction

The most recent assessment undertaken by the Intergovernmental Panel on Climate Change (IPCC) reached a number of conclusions concerning global climate change, two of which stated that "Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level" and that "Most of the observed increases in global average temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations". These observed changes in climate are as a result of a global average surface air temperature increase over the 20th century of about 0.6°C. In contrast to these observed changes, global average surface air temperature is projected to increase between 1.4°C and 5.8°C by 2100, relative to 1990.

Following recommendations outlined by the IPCC, Barrow (2009) constructed scenarios of climate change using the most recent global climate model (GCM) results available. Scenarios for key climate variables are summarized here. GCMs are three-dimensional mathematical models of the Earth-atmosphere system driven by changes in atmospheric composition through the effect of these changes on the radiation balance of this system. It is not known how atmospheric composition will change in the future, since it is dependent on a number of factors, including population and economic growth and energy use. Thus, GCM experiments are usually undertaken using a number of different greenhouse gas emissions scenarios, spanning a range of possible socio-economic futures. For this study, results were available from GCM experiments undertaken at fourteen different climate modelling centres using three emissions scenarios (B1, A1B and A2). The output from GCMs is still not sufficiently reliable to be used directly as climate input into impacts studies so it is necessary to construct scenarios of climate change. These scenarios were constructed by determining the changes in average climate for the 30-year periods centered on the 2020s (2010-2039), 2050s (2040-2069) and 2080s (2070-2099), relative to the 1961-1990 baseline period.

For this analysis, Saskatchewan was divided into two regions - forest and grassland as shown in Figure 6. Since there are a large number of GCM experiments available, a sub-set of climate change scenarios was selected for use based on changes in an annual moisture index which combines the effect of temperature and precipitation. A total of five scenarios were selected to represent the smallest, largest and median changes in annual moisture index. For the forest region, these scenarios were from the Bjerknes Centre for Climate Research, Norway (BCM2 B1), the UK Meteorological Office (HadCM3 A1B) and the National Institute for Environmental Studies, Japan (MIMR B1), respectively, and from the Canadian Centre for Climate Modelling and Analysis (CGCM3_T47_2 A1B), the Geophysical Fluid Dynamics Laboratory, USA (GFCM20 B1) and, again, from the National Institute for Environmental Studies, Japan (MIMR B1), respectively, for the grassland region. For each GCM only mean temperature and precipitation information was available and so climate change scenarios were constructed for these variables.

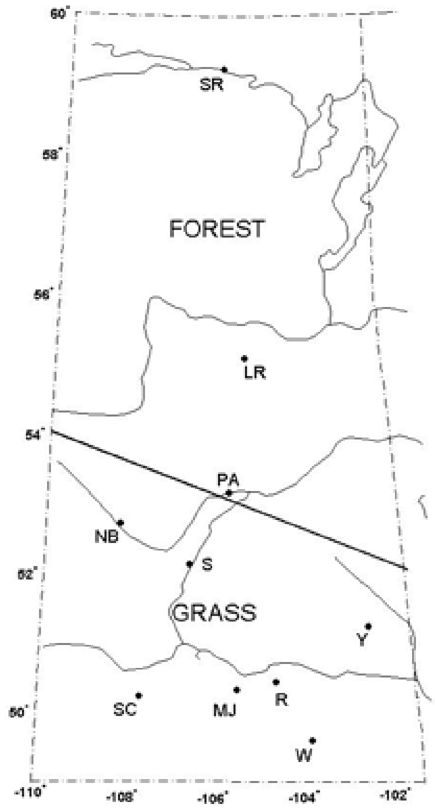


Figure 6: Map of Saskatchewan showing boundary (black line) between forest and grassland regions and major towns: SR – Stony Rapids; LR – La Ronge; PA – Prince Albert; NB – North Battleford; S – Saskatoon; Y – Yorkton; SC – Swift Current; MJ – Moose Jaw; R – Regina; W – Weyburn.

Climate Change Scenarios

Given the number of scenarios and variables being considered, Barrow (2009) necessarily focused on annual results. For the forest region, scatter plots of mean temperature change versus precipitation change (Figure 7) indicate that by the 2080s, annual changes in precipitation are positive in this region for all climate change scenarios considered in this analysis. For the 2020s and 2050s, a small number of scenarios indicate decreased precipitation, but these decreases are very slight – only around 5% in the 2020s and about 2% in the 2050s. Changes in mean annual temperature are positive – between 0 and 3°C in the 2020s, 1 to 5°C in the 2050s and between 2 and 7°C for the 2080s. The seasonal picture for the 2050s (Figure 8) indicates that the largest spread in scenario results occurs in winter, with temperature changes between 0 and 7°C and mostly positive precipitation changes (up to 30%). For spring, the picture is similar, although the temperature increases are not quite as large. The summer and fall scatter plots show some scenarios with larger precipitation decreases – as much as 10% in summer and around 5% in the fall.

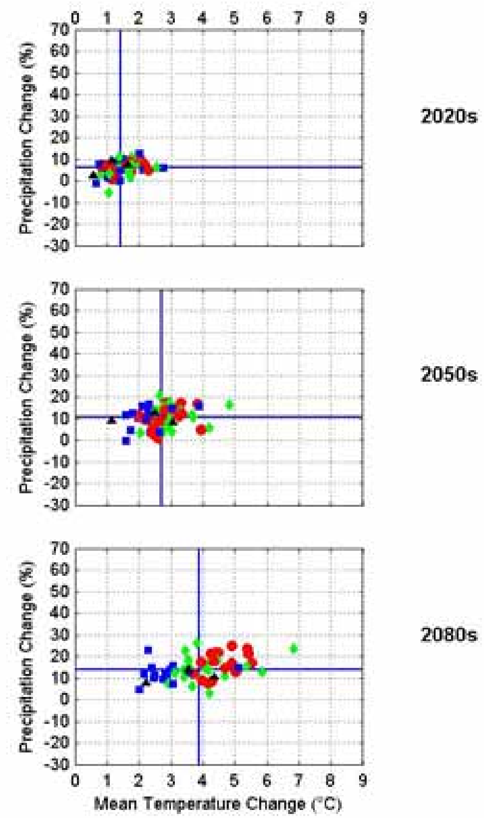


Figure 7: Scatter plots indicating annual changes in mean temperature (°C) and precipitation (%) for the forest region of Saskatchewan for the 2020s, 2050s and 2080s. The different coloured symbols represent different emissions forcings: green diamonds – A1B, blue squares – B1, red circles – A2. Black triangles indicate the three scenarios selected based on minimum, maximum and median change in annual moisture index. Blue lines indicate the median changes in mean temperature and precipitation for this suite of scenarios.

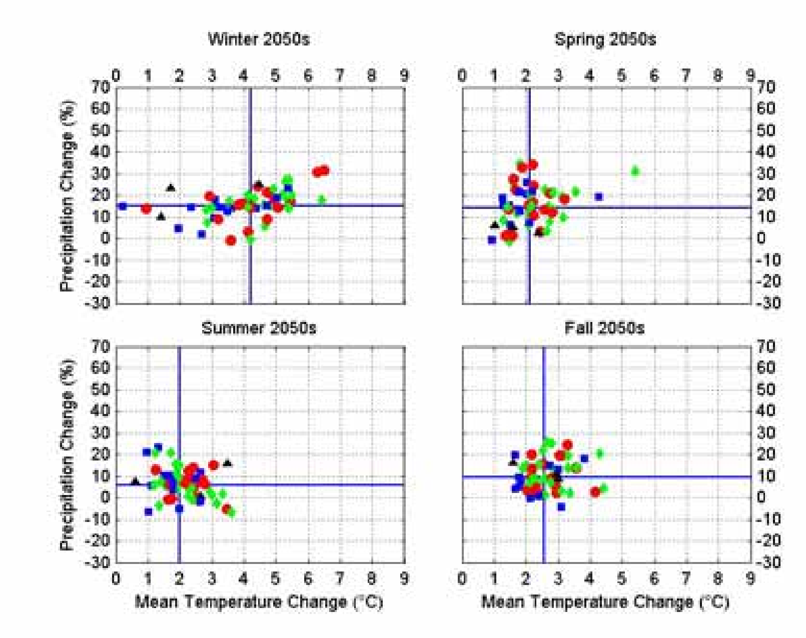


Figure 8: Scatter plots indicating seasonal changes in mean temperature (°C) and precipitation (%) for the forest region of Saskatchewan for the 2020s, 2050s and 2080s. The different coloured symbols represent different emissions forcings: green diamonds – A1B, blue squares – B1, red circles – A2. Black triangles indicate the three scenarios selected based on minimum, maximum and median change in annual moisture index. Blue lines indicate the median changes in mean temperature and precipitation for this suite of scenarios.

In summary, for the 2050s, the forest region of Saskatchewan is projected to experience increases in annual mean temperature of between 0.5 - 1.0°C (for the scenario based on the smallest change in annual moisture index) and 3.0 - 3.5°C (for the scenario based on the median change in annual moisture index). Changes in annual precipitation are between 0 and +10% for all three scenarios for the 2050s, although the median scenario indicates slightly higher increases (+10 to +20%) along the western and northern boundaries of the forest region.

When compared with the forest region, the scatter plots for the grassland region (Figure 9) give some larger decreases in annual mean precipitation, with some decreases still projected for the 2080s. For the 2020s, temperature increases are between 0.5 and 3.0°C, between 1 and 5°C for the 2050s and between 2 and 6.5°C for the 2080s. The range of changes in annual mean precipitation are similar for the 2020s and 2050s, between -10% and +25%, compared to between -5% and +35% for the 2080s. On a seasonal basis for the 2050s (Figure 10), scenarios projecting decreases in precipitation occur in all seasons. For summer and fall, about half the scenarios project precipitation decreases by as much as 20 or 30%. The range of temperature increase is largest in winter and spring (between 1 and 6°C), compared to summer and fall (1 to 4°C).

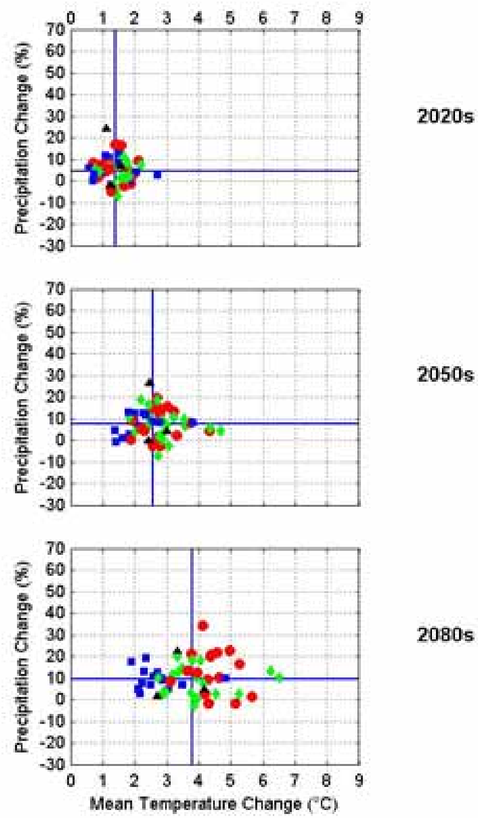


Figure 9: Scatter plots indicating annual changes in mean temperature (°C) and precipitation (%) for the grassland region of Saskatchewan for the 2020s, 2050s and 2080s. The different coloured symbols represent different emissions forcings: green diamonds – A1B, blue squares – B1, red circles – A2. Black triangles indicate the three scenarios selected based on minimum, maximum and median change in annual moisture index. Blue lines indicate the median changes in mean temperature and precipitation for this suite of scenarios.

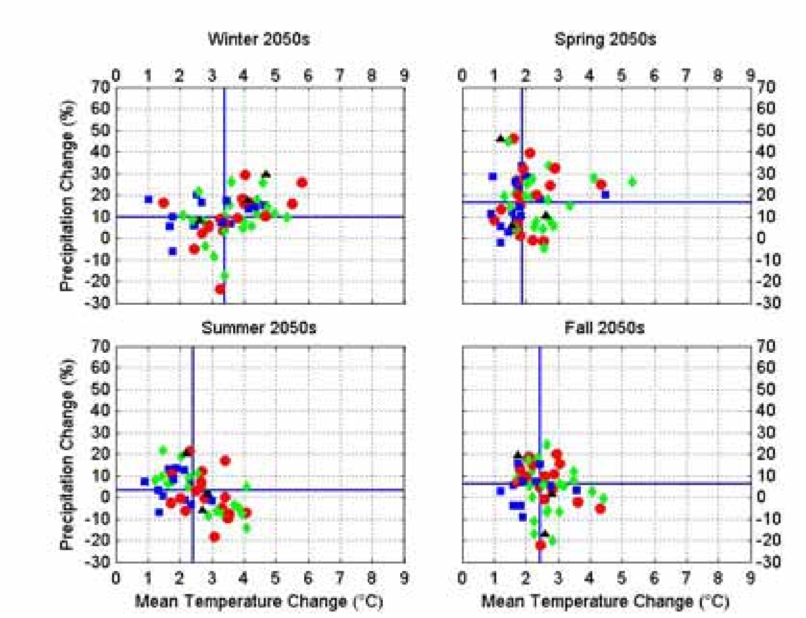


Figure 10: Scatter plots indicating seasonal changes in mean temperature (°C) and precipitation (%) for the grassland region of Saskatchewan for the 2020s, 2050s and 2080s. The different coloured symbols represent different emissions forcings: green diamonds – A1B, blue squares – B1, red circles – A2. Black triangles indicate the three scenarios selected based on minimum, maximum and median change in annual moisture index. Blue lines indicate the median changes in mean temperature and precipitation for this suite of scenarios.

In summary, for the 2050s, the grassland region of Saskatchewan is projected to experience increases in annual mean temperature of between 1.5 - 2.0°C (for the scenario based on the smallest change in annual moisture index) and 2.5 - 3.0°C (for the scenario based on the median change in annual moisture index). Precipitation changes are similar across all time periods, generally between 0 and +10%. For the 2050s, the scenario based on the largest change in annual moisture index indicates that there are some areas of precipitation decrease (between 0 and -10%) in the south-east portion of the grassland region. The scenario based on the smallest change in annual moisture index indicates general increases in precipitation of between 10 and 20% by the 2050s, although these increases are slightly lower (between 0 and 10%) in the south-east portion of the region.

Climate Scenarios

By combining these climate change scenarios with a high resolution 1961-1990 baseline climatology, Barrow (2009) construct climate scenarios for Saskatchewan for minimum, mean and maximum temperatures and precipitation, as well as for the following derived variables: degree days > 5°C, degree days > 18°C (cooling degree days), degree days < 18°C (heating degree days) and annual moisture index for the 2020s, 2050s and 2080s. Results for a few of these variables are presented here as maps for the whole province and as plots for Stony Rapids, Prince Albert, La Ronge, Regina, Saskatoon, North Battleford, Yorkton, Weyburn, Moose Jaw and Swift Current.

Figures 11-13 show temperatures, precipitation and annual moisture index for the 2050s for the entire province but for scenarios selected according to AMI change over the forest region of Saskatchewan. Thus even though scenarios are maps for the entire province, these maps are most applicable to the forested region. For this region, annual mean temperature increases over time at all three sites (Prince Albert, La Ronge and Stony Rapids) plotted in Figures 14-16. By the 2020s, the projected future climate range for La Ronge (-0.01 to 0.98°C) is as warm as baseline conditions at Prince Albert (0.58°C). For Stony Rapids, it is only by the 2080s that the projected annual mean temperature range (-1.91 to 0.4°C) approaches that of baseline conditions at La Ronge (-0.45°C). Precipitation is projected to increase across all sites and all time periods (Figure 15). Prince Albert (406 mm) and Stony Rapids (391 mm) currently receive less precipitation than La Ronge (494 mm). By the 2080s, Prince Albert is projected to receive between 423 and 456 mm, La Ronge between 514 and 547 mm and Stony Rapids between 419 and 446 mm. The annual moisture index gives an indication of moisture availability for plant growth as function the ratio of temperature to precipitation. This index increases across all time periods for all three forest sites. By the 2080s, the index values are projected to increase by at least 1 degree day/mm at each site (Figure 16) suggesting the potential for higher moisture stress. The scenario range for La Ronge (2.96-3.77) and Stony Rapids (2.67-3.86) for this time period encompasses baseline conditions at Prince Albert (3.41).

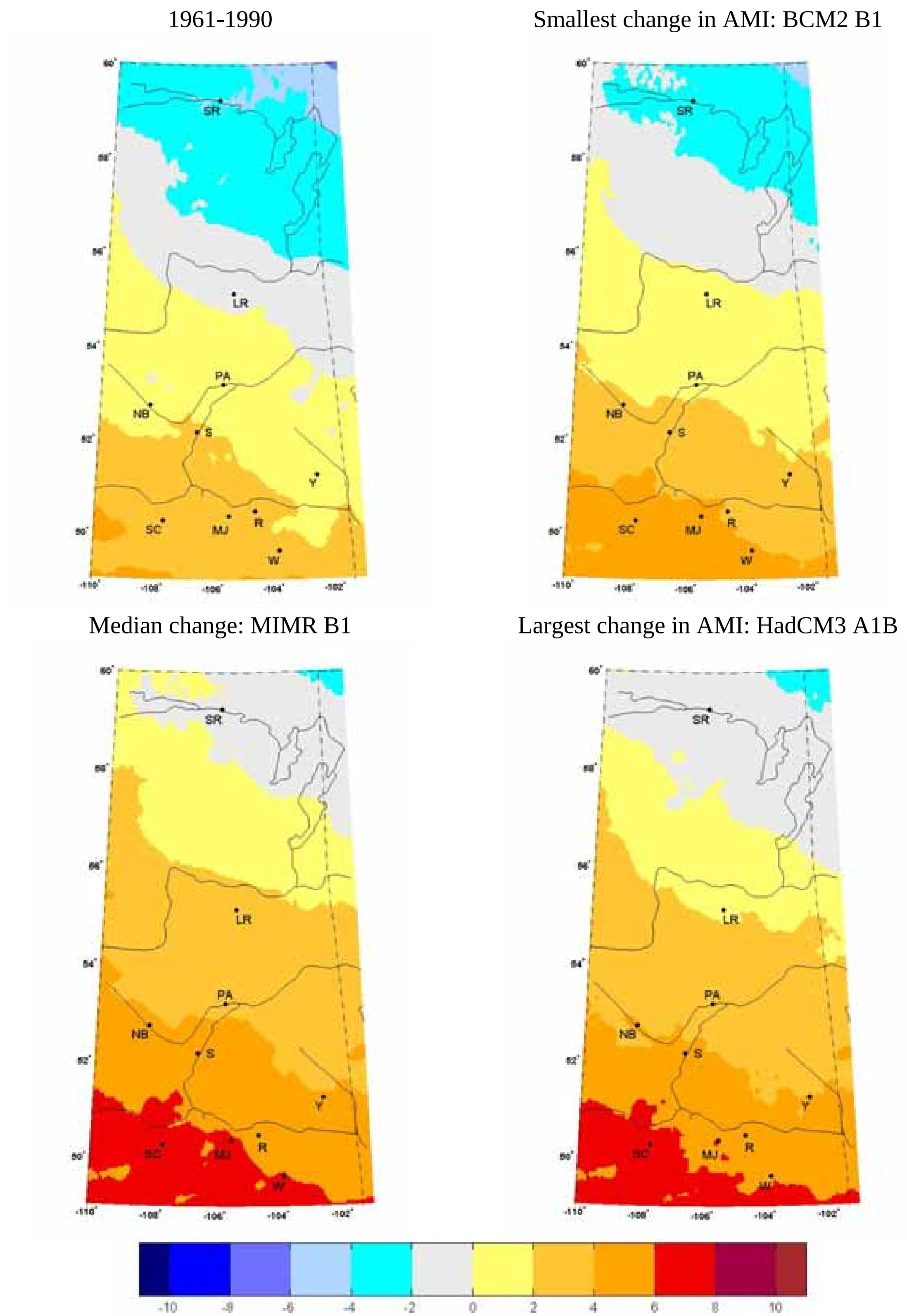


Figure 11: Annual mean temperature (°C) for the 2050s, selected based on AMI change over forest region of Saskatchewan.

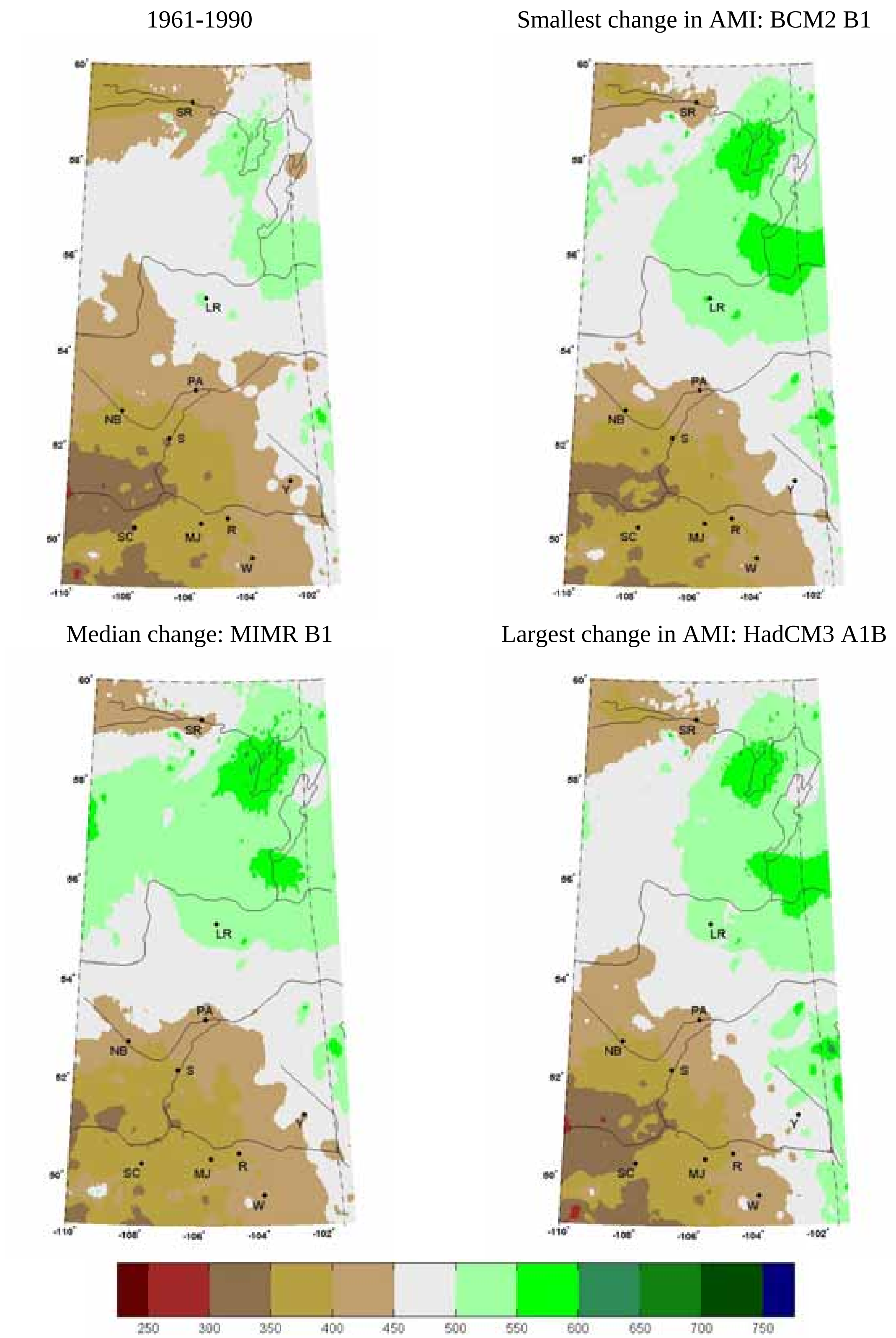


Figure 12: Annual precipitation (mm) for the 2050s, selected based on AMI change over forest region of Saskatchewan.

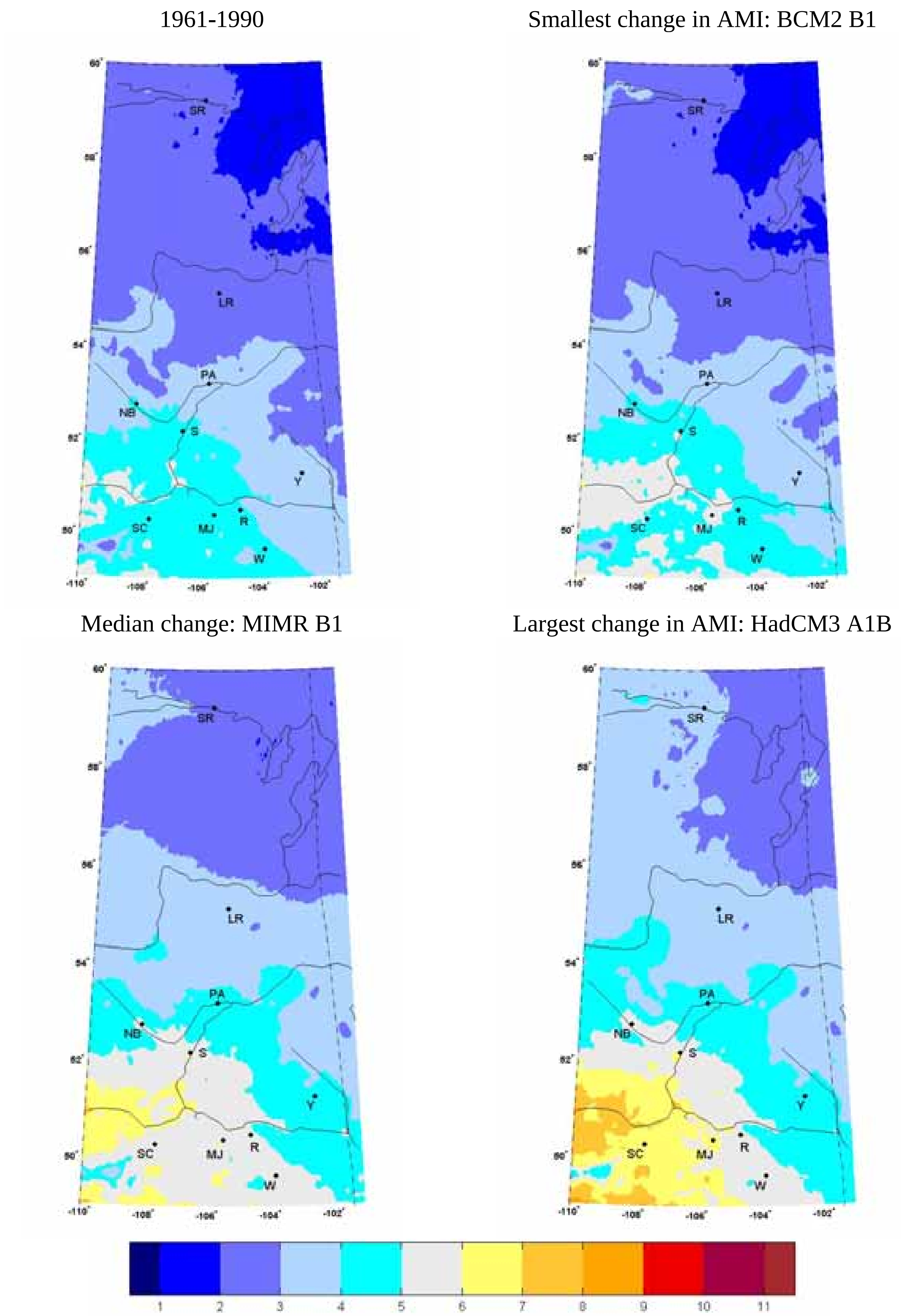


Figure 13: Annual moisture index for the 2050s, selected based on AMI change over forest region of Saskatchewan.

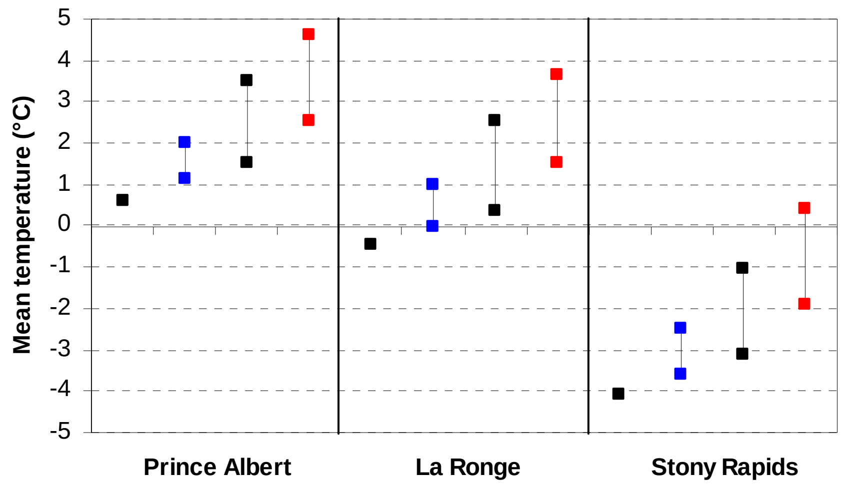


Figure 14: Annual mean temperature (°C) for three selected sites in the forest region of Saskatchewan. At each site there are four blocks of data: 1961-1990 baseline (black square), and the scenario ranges for the 2020s (blue high-low lines), the 2050s (black high-low lines) and the 2080s (red high-low lines). The scenario range has been calculated from the results for the three selected scenarios.

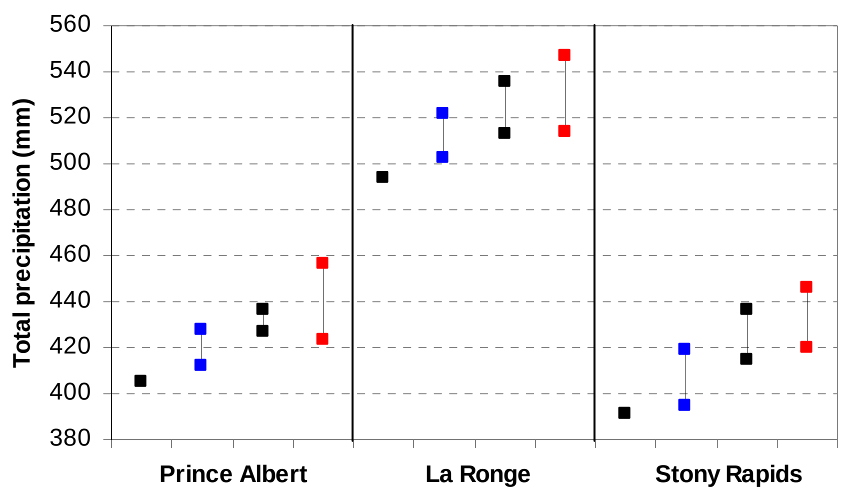


Figure 15: Annual precipitation total (mm) for three selected sites in the forest region of Saskatchewan. At each site there are four blocks of data: 1961-1990 baseline (black square), and the scenario ranges for the 2020s (blue high-low lines), the 2050s (black high-low lines) and the 2080s (red high-low lines). The scenario range has been calculated from the results for the three selected scenarios.

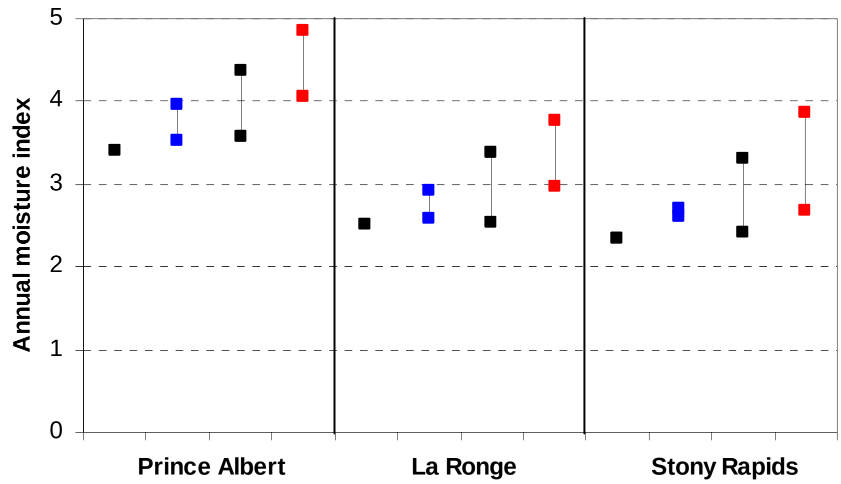


Figure 16:Annual moisture index for three selected sites in the forest region of Saskatchewan. At each site there are four blocks of data: 1961-1990 baseline (black square), and the scenario ranges for the 2020s (blue high-low lines), the 2050s (black high-low lines) and the 2080s (red high-low lines). The scenario range has been calculated from the results for the three selected scenarios.

Figures 17-19 show temperatures, precipitation and annual moisture index for the 2050s for the entire province but for scenarios selected according to AMI change over the grassland region of Saskatchewan. Thus even though scenarios are mapped for the entire province, these maps are most applicable to the grassland region. For this region, annual mean temperature at the seven sites increases over time such that by the 2020s, the annual mean temperature is at least 1°C warmer than baseline conditions at all sites, and for Yorkton 3°C warmer (1.3°C compared with 4.3°C). By the 2080s, the projected annual mean temperature is at least double that of baseline conditions (Figure 20). Increases in annual precipitation totals are projected over time at all seven grassland sites (Figure 21). For annual moisture index (Figure 22), increases occur across all sites and all time periods, indicating a rise in the ratio of temperature and heat to precipitation and moisture. Yorkton and North Battleford currently exhibit the lowest annual moisture index values (3.4 and 4.2 degree days/mm, respectively). By the 2080s, these values have increased to between 3.9 and 4.7 degree days/mm for Yorkton and to between 4.7 and 5.6 degree days/mm for North Battleford. Moose Jaw and Saskatoon currently exhibit the largest baseline values (both 4.7 degree days/mm). By the 2080s, annual moisture index values are projected to be between 5.3 and 6.4 degree days/mm for Moose Jaw and between 5.2 and 6.2 degree days/mm for Saskatoon.

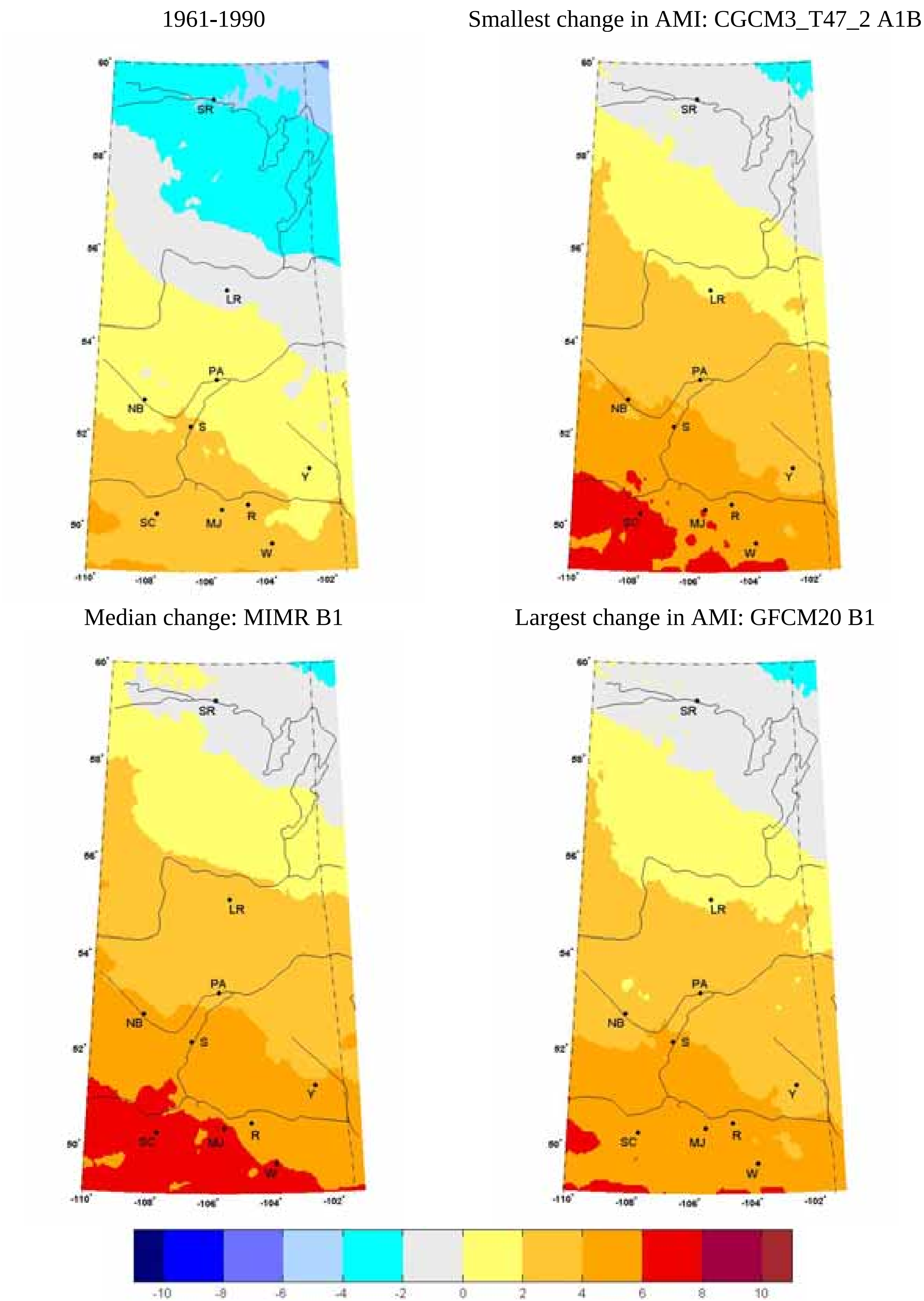


Figure 17: Annual mean temperature (°C) for the 2050s, selected based on AMI change over grassland region of Saskatchewan.

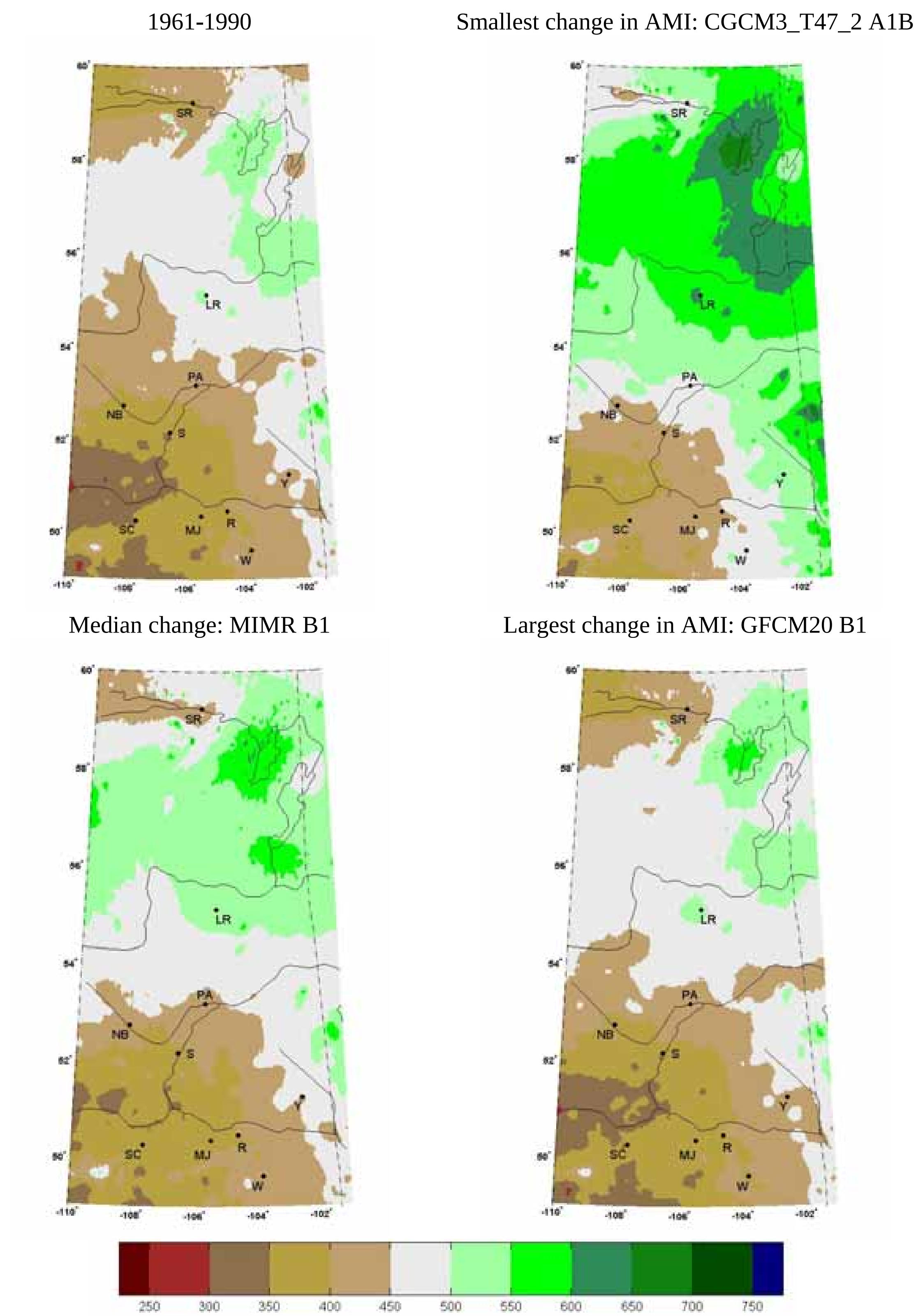


Figure 18: Annual precipitation total (mm) for the 2050s, selected based on AMI change over grassland region of Saskatchewan.

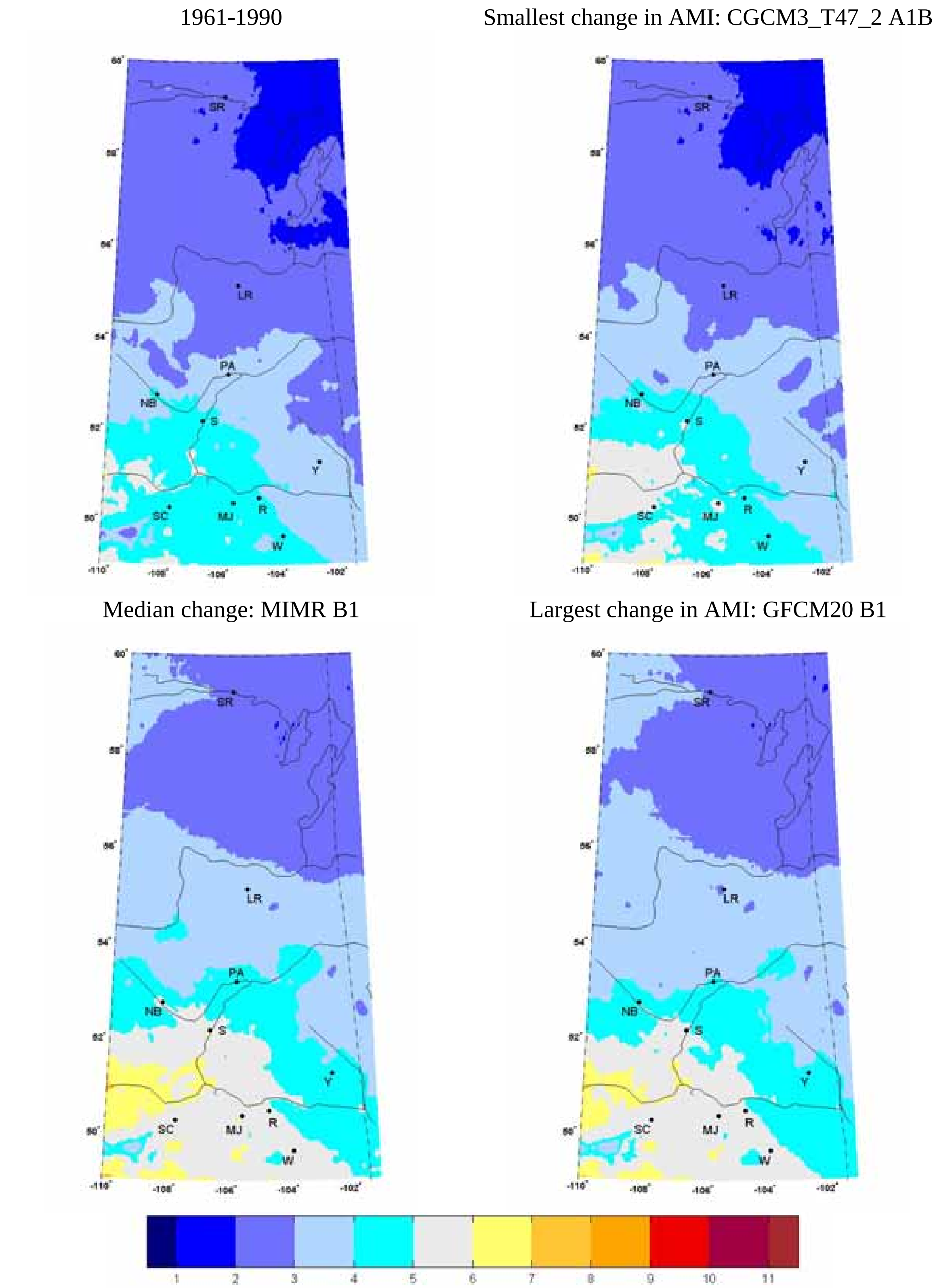


Figure 19: Annual moisture index for the 2050s, selected based on AMI change over grassland region of Saskatchewan.

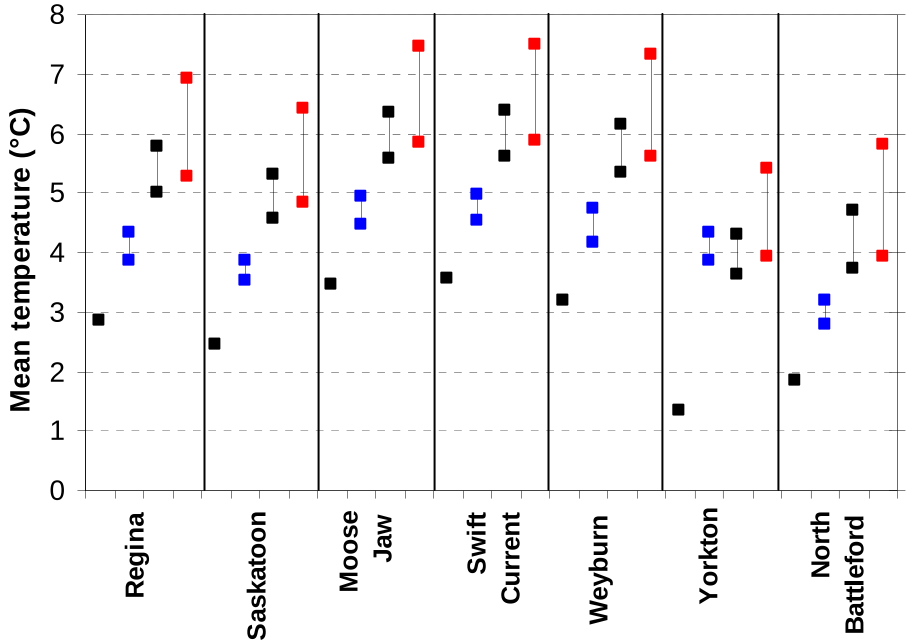


Figure 20: Annual mean temperature (°C) for seven selected sites in the grassland region of Saskatchewan. At each site there are four blocks of data: 1961-1990 baseline (black square), and the scenario ranges for the 2020s (blue high-low lines), the 2050s (black high-low lines) and the 2080s (red high-low lines). The scenario range has been calculated from the results for the three selected scenarios.

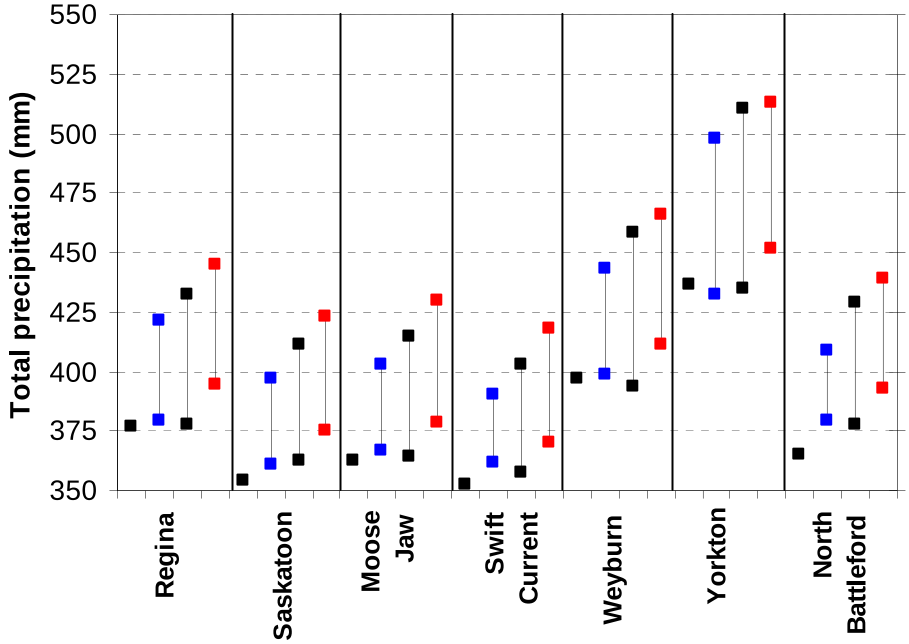


Figure 21: Annual precipitation total (mm) for seven selected sites in the grassland region of Saskatchewan. At each site there are four blocks of data: 1961-1990 baseline (black square), and the scenario ranges for the 2020s (blue high-low lines), the 2050s (black high-low lines) and the 2080s (red high-low lines). The scenario range has been calculated from the results for the three selected scenarios.

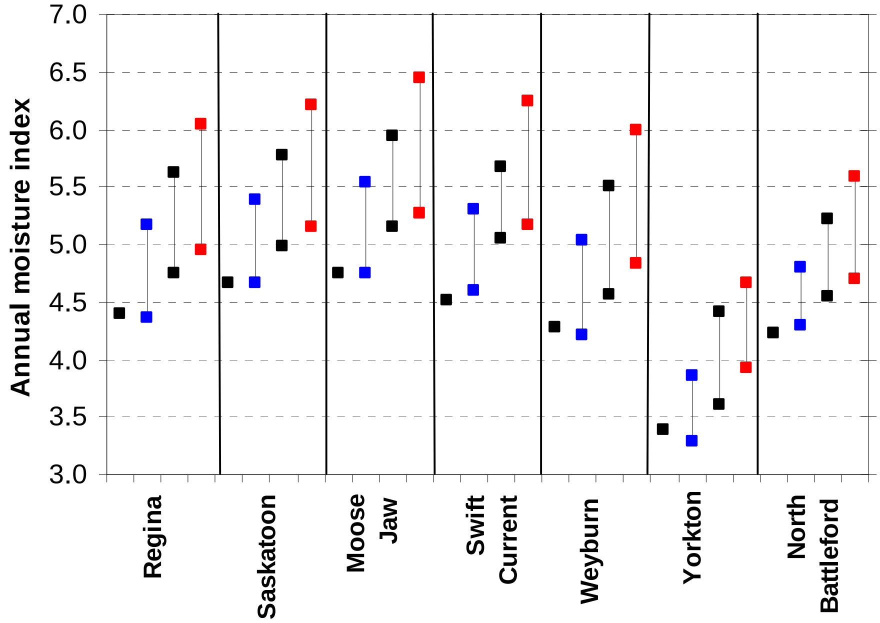


Figure 22: Annual moisture index for seven selected sites in the grassland region of Saskatchewan. At each site there are four blocks of data: 1961-1990 baseline (black square), and the scenario ranges for the 2020s (blue high-low lines), the 2050s (black high-low lines) and the 2080s (red high-low lines). The scenario range has been calculated from the results for the three selected scenarios.

WATER RESOURCES

Introduction

Since the publication of the Intergovernmental Panel on Climate Change's 2007 report there can be little doubt amongst policy makers that we are undergoing rapid climate change and that the degree of climate change is expected to continue to increase in the near to medium range future, despite any efforts made to reduce greenhouse gas emissions or to sequester carbon dioxide. Saskatchewan's environment, ecology and economy are water dependent and so are strongly impacted by hydrological cycling and water supply fluctuations because of our extensive periods of water shortage and excess, our strong seasonality in surface water supply and our general cool semi-arid to cold sub-humid climate. Many of our ecological and economic activities use close to or all available water and so we are particularly vulnerable to further variations in water resources due to climate change. For instance, our two major economic disasters in the province have been due to lack of available water in the drought of the 1930s and the recent drought of 1999-2004. In 2001-2002, the national loss of $6 billion in Gross Domestic Product (GDP) and the disappearance of 41,000 jobs due to lack of water largely occurred in Saskatchewan. It is therefore prudent to examine what features of our climate, hydrology and water resources make our response to changes in water supply potentially unique, what are the anticipated impacts of climate change on our water resources, and what water management options are available or should be considered to minimize the risk caused by climate change.

The purpose of this section of the impact assessment report is to:

i) document the expected impacts of climate change on Saskatchewan's water resources, and
ii) outline the options for adaptation of water resource management practices, policies and infrastructure to minimize the risk associated with the impacts of climate change.

These objectives are addressed with an overview of Saskatchewan's unique hydrological and water resources characteristics, a review of anticipated climate change in the region, an assessment, based on the most up to date science, of the most likely impacts of climate change on water resources for the South Saskatchewan River and for a representative prairie stream in southwest Saskatchewan, and an interpretation of this information in outlining options for adaptation of future water resources management practices, policies and infrastructure in the context of risk management. A review and bibliography of recent literature on the impacts of climate change on water resources in the Province is provided in Appendix 1. The focus is on the prairie region of the province where most of the population is co-located with limited water resources.

Review of Saskatchewan Hydrology and Water Resource Characteristics

Overview

Saskatchewan is characterized by relatively low precipitation especially in the southwest part due to the atmospheric flow barrier imposed by the Rocky Mountains and experiences frequent water deficits and low moisture reserves (Agriculture and Agri-Food Canada 1998). Annual precipitation in the prairie region of Saskatchewan ranges from 300-400 mm (Pomeroy *et al*. 2007), about one third of which occurs as snowfall (Gray and Landine 1988). Saskatchewan is a cold region and exhibits classical cold regions hydrology with continuous snowcover and frozen soils over much of the winter. Great variations in hydrology exist across the Province, with fairly well-drained, semi-arid basins in the southwest part and with many wetlands and lakes in the relatively wetter north, central and eastern parts.

The hydrology of Saskatchewan is characterized by:

- long periods of winter (usually 4-6 months) with occasional mid-winter melts (frequent in the southwest and infrequent in the northeast), with the snowcover modified by wind redistribution and sublimation of blowing snow on the prairies and modified by snow interception in the boreal forest,
- high surface runoff from spring snowmelt as a result of frozen mineral soils at the time of the relatively rapid release of water from snowpacks (Gray *et al*. 1985),
- deep prairie soils characterized by good water-holding capacity and high unfrozen infiltration rates (Elliott and Efetha 1999) and shallow boreal soils or organic layers with poor water holding capacities and high infiltration rates (Elliott *et al*. 1998),
- most rainfall occurring in spring and early summer from large frontal systems and the most intense rainfall in summer from convective storms over small areas (Gray 1970),
- very low levels of soil moisture, plant growth, actual evaporation and runoff from mid-summer to fall due to low rainfall in the prairie region (Granger and Gray 1989), with adequate soil moisture supplies in central to northern Saskatchewan (Pomeroy *et al*. 1997),
- poorly-drained stream networks in the prairies such that large areas are internally drained where local runoff does not contribute to the major river systems (Martin 2001).

Prairie hydrological cycle

The main processes in the prairie hydrological cycle are shown in Figure 23. Snow is an important water resource on the Canadian Prairies. Approximately one third of annual precipitation occurs as snowfall. There are three scales describing the spatial variability of snow accumulation – micro (10 to 100 m), meso (100 m to 10 km), and macro (10 to 1,000 km) (Pomeroy and Gray 1995).

Saskatchewan prairie snow accumulation is highly heterogeneous at micro and meso scales, due to wind redistribution of snow, also known as blowing snow. Redistribution is primarily from open, well exposed sites to sheltered or vegetated sites (Pomeroy and Gray 1995). Blowing snow transport forms snowdrifts, usually in sloughs, drainage channels or river valleys; this windblown snow provides an important source of runoff and controls streamflow peak and duration (Pomeroy *et al*. 2007, Fang and Pomeroy 2008). Seasonal sublimation of blowing snow is equivalent to 15%-40% of seasonal snowfall on the Canadian Prairies (Pomeroy and Gray 1995). Blowing snow in the open environments can transport and sublimate or redistribute as much as 75% of annual snowfall from open, exposed fallow fields in southern Saskatchewan; how much of this can end up in a drift depends on field size, temperature, humidity and wind speed (Pomeroy and Gray 1995).

Snowmelt is one of the most important hydrological processes in Saskatchewan. Melting water from snow recharges the soil moisture and groundwater storage through infiltration and replenishes reservoirs, lakes, and rivers through surface runoff (Norum *et al.* 1976). The amount of water from snowmelt is controlled by energy exchange at the snow surface, and meltwater is produced when the snowpack is at a temperature of 0°C (Male and Gray 1981). Typically, 80% or more of prairie runoff is generated from snowmelt (Gray and Landine 1988).

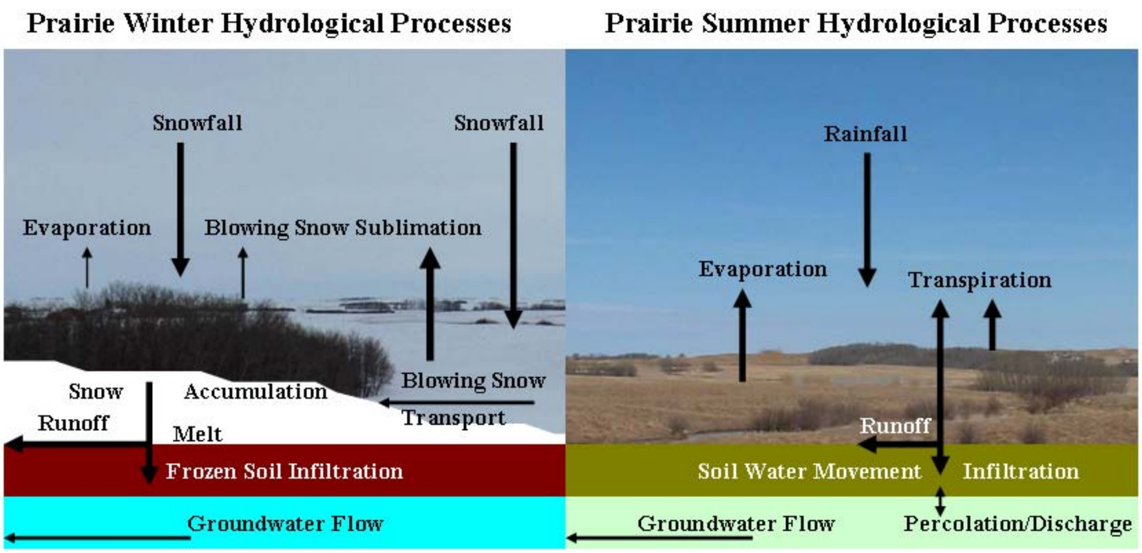


Figure 23. Prairie hydrological cycle: left – winter processes, right – summer processes

Rainfall occurs primarily from May to early July and provides water for the growth of crops. Most of the rainfall is consumed by seasonal evaporation, which leads to little surface runoff during the summer period. A primary mechanism for most rainfall events during early summer on the Prairie is the frontal weather system, while the most intense short duration rainfalls are associated with local convective storms (Gray 1970).

Infiltration is the process by which water flows through the soils and is strongly affected by soil properties, moisture content and the occurrence of frozen soils. Infiltration into frozen soils is controlled by the amount of snow available to melt, the soil moisture content in the previous fall and the occurrence of major melt events in mid-winter that can seal the frozen soil with a superimposed ice layer (Pomeroy *et al*. 2007). Variations in infiltration to frozen soils can exert a strong control on runoff generation from snowmelt; runoff efficiencies are near 100% over saturated frozen soils or those with superimposed ice layers and drop to near 0% for severely cracked or highly porous and dry frozen soils (Gray *et al*. 2001). In the summertime, infiltration from rainfall is generally enhanced when the soil is thawed and this usually leads to minimal surface runoff. Limited runoff is due to both infrequent rainfalls of short duration as well as the high infiltration capacity of prairie soils which are most often unsaturated at the surface. Exceptions are due to intense summer convective storms, but these normally occupy small areas and so have little impact on overall water resources.

Evapotranspiration (evaporation and transpiration) is driven by the net radiation to the surface and by convection of water vapour from wet surfaces to the relatively dry atmosphere. During summer, evapotranspiration consumes most rainfall on the prairies and occurs quickly via direct wet surface evaporation from water bodies, rainfall intercepted on plant canopies and wet soil surfaces; it occurs more slowly as unsaturated surface evaporation from bare soils and as transpiration from plant stomata (Granger and Gray 1989). Evaporation, directly from bare soils and indirectly by transpiration, withdraws soil moisture reserves and eventually results in soil desiccation if there are no further inputs of water from rain or groundwater outflows. On average, seasonal evapotranspiration loss is close to seasonal rainfall in Saskatchewan, and less than rainfall in exceptionally wet or cool years, especially in the east and north of the agricultural region. It must be emphasized that actual evapotranspiration is almost always less than potential evapotranspiration and that this difference increases with aridity (Granger and Gray 1989). Studies that rely on potential evapotranspiration (*e.g.* Schindler and Donahue 2006) are not useful in water balance analyses and hydrological flow predictions in this dry environment, because potential rates display inverse behaviour to actual rates and cannot be directly related to any water resource variable (Armstrong *et al*. 2008, Fernandes *et al*. 2009).

Groundwater recharge usually occurs in depressions such as sloughs, wetlands and pothole lakes through infiltration into the soil columns and then deep percolation below the rooting depth (Hayashi *et al*. 2003). Much of the water that infiltrates is exhausted by evapotranspiration before percolation to deep groundwater can occur (Parsons *et al*. 2004). This leads to very low and steady deep groundwater flow rates; 5-40 mm is a reported range of annual groundwater recharge rates in the prairie (van der Kamp and Hayashi 1998). In general, groundwater supplies are poorly connected to surface water resources because of heavy glacial till deposits overlying the major aquifers and so groundwater has little impact on lakes or base flow with the exception of certain upland streams (*e.g.* in the Cypress Hills).

Prairie runoff generation

The Canadian Prairies are characterized by numerous small depressions such as sloughs, wetlands and dugouts. These water bodies are often internally drained resulting in closed catchments (Hayashi *et al.* 2003), and there is a lack of connection amongst them as well as to the main prairie streams. Where there is internal drainage in normal conditions these catchments are termed non-contributing areas (Godwin and Martin 1975) and are illustrated in Figure 24. Other areas do drain to streams.

The seasonality of Prairie surface water supply is marked. In fall and winter, the water is stored as snow, and lake and ground ice; in early spring, the water supply is derived from rapid snowmelt resulting in most runoff; in late spring and early summer, water is stored as soil moisture and surface water, sustained by rainfall. Snowmelt water contributes 80% or more of annual surface runoff for Prairie streams (Gray and Landine 1988). However, due to the aridity and gentle topography of the prairie, natural drainage systems are poorly developed, disconnected and sparse, resulting in surface runoff that is both infrequent and spatially restricted (Gray 1970). Recent drainage activities have increased runoff to streams and wetlands in some regions.

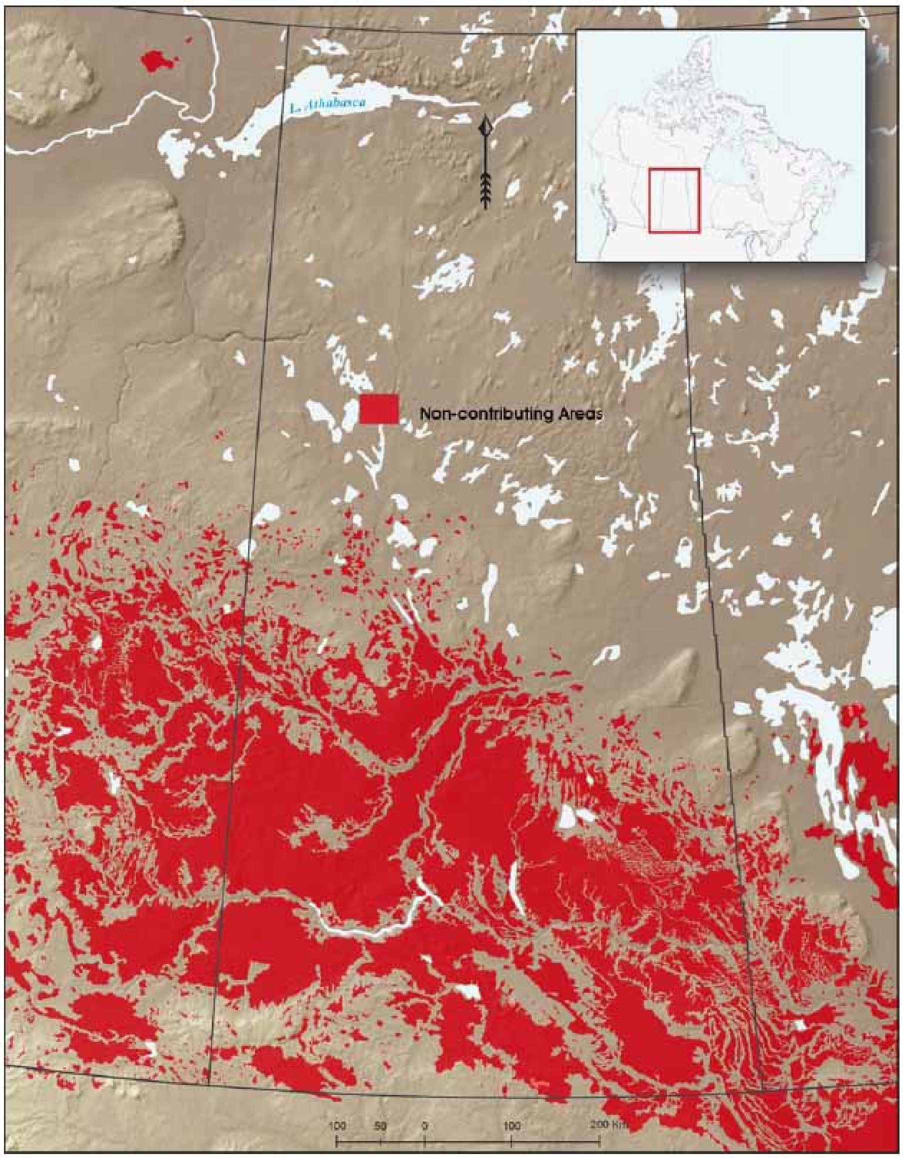


Figure 24. Non-contributing areas of drainage basins as delineated by PFRA (image from Pomeroy *et al*. 2007).

Saskatchewan's hydrology is characterized by low precipitation which mostly evaporates leaving little for runoff. This means that local-scale water resources are quite limited and very sensitive to changes in climate and land cover. The perception of plenty caused by seeing stored water in lakes, snow covers, and wetlands does not match the reality of low flow rates in the hydrological cycle.

An example of a prairie streamflow regime is that of Smith Creek in the eastern part of the province. The creek drains up to about 400 km^2 and normally peaks during and just after snowmelt, becoming dry by midsummer, and remaining so until the subsequent spring (Figure 25). It is highly variable from year to year with daily peak flows of almost 24 m^3/s during flood to minimal yearly flow in times of drought. Streams with such intermittent and variable flow regimes are not normally usable for water supply without impoundment as reservoirs. However, reservoir management of such variable streamflow is challenging in periods of extreme drought or water excess. Hence few prairie streams are managed for substantial water consumption or irrigation, with the perception that the most reliable water supply comes from groundwater and rivers that originate in the Rocky Mountains in Alberta.

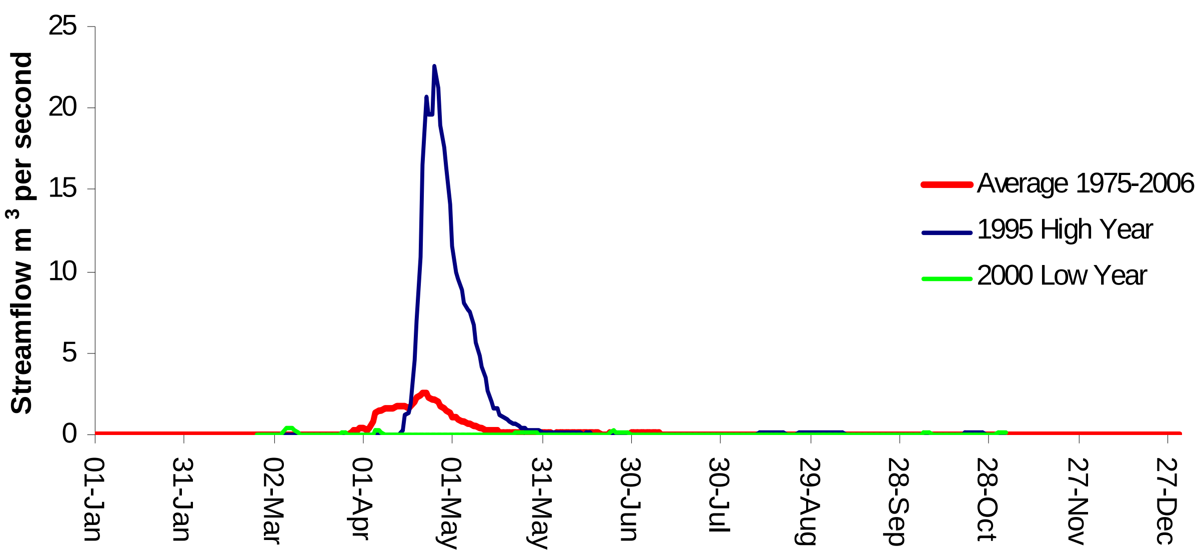


Figure 25. Annual hydrograph of a small prairie stream, Smith Creek near Langenberg.

Saskatchewan rivers and their flows

Figure 26 shows the major rivers and their mean annual discharge over the province. In the prairie region, the vast majority of streamflow in these rivers is derived from runoff upstream in the Rocky Mountains where it is dominated by snowmelt (Lapp *et al*. 2004, Stewart *et al*. 2007). Moving eastward and northward there is increased local runoff which makes some contribution to streamflow, but this never exceeds what is 'imported' from the mountains. The annual flow regime of the North Saskatchewan River and of the South Saskatchewan River upstream of Lake Diefenbaker is dominated in the winter by the formation and melt of river ice, during the spring by the melting of snow on the prairies and during the summer by snowmelt in the mountains.

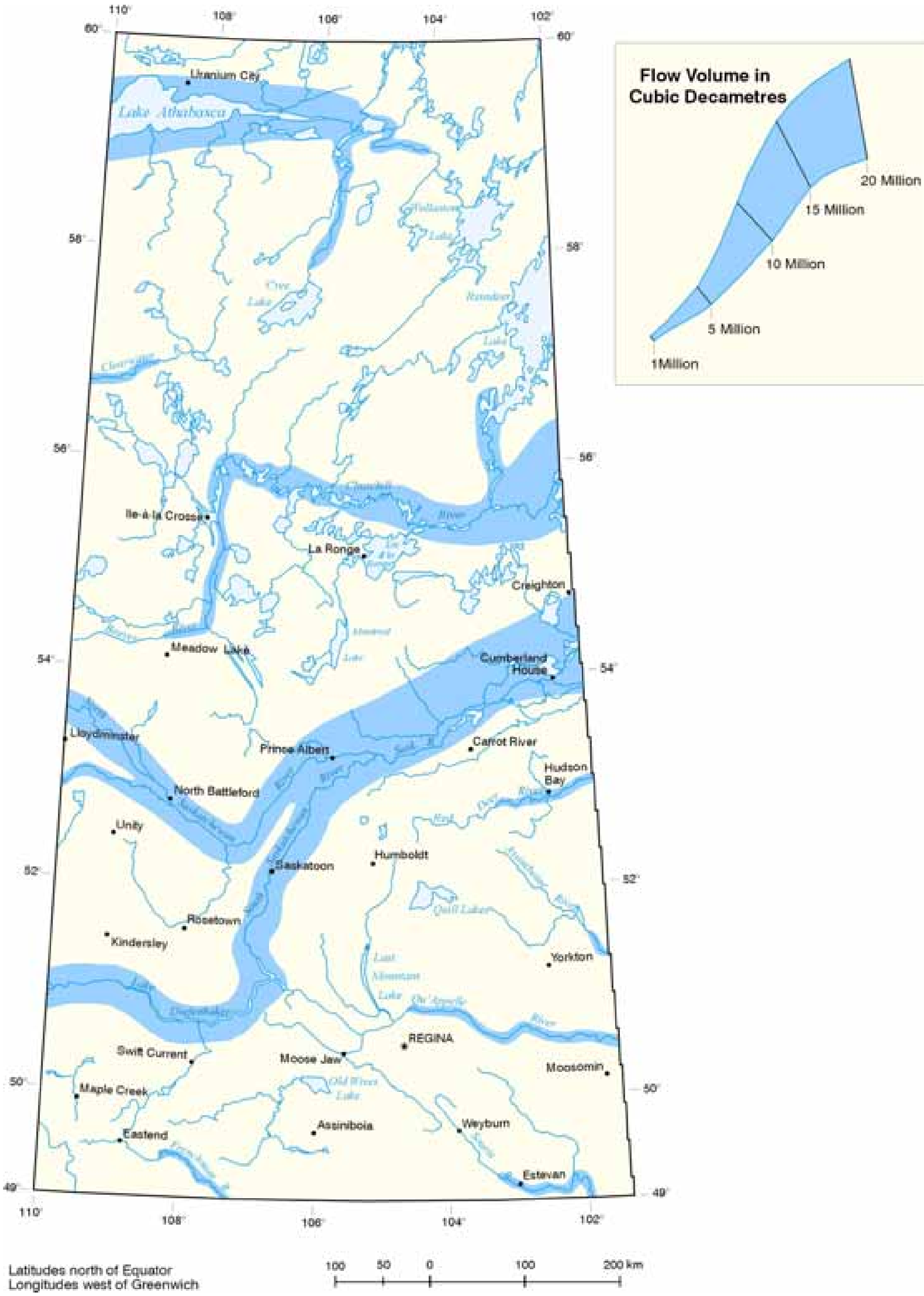


Figure 26. Map of Saskatchewan with annual discharge along the main rivers. © University of Saskatchewan, 2000.

Within Saskatchewan, the only significant tributary to the South Saskatchewan River is Swift Current Creek, which contributes less than 1% of the flow. The melt of glacier ice has a minimal effect on the flows of the North and South Saskatchewan Rivers entering Saskatchewan – most flow is derived from mountain snowmelt (Comeau 2009). The Qu'Appelle River had a natural flow regime that was dominated by prairie spring runoff but is now substantially modified by water inflows from Lake Diefenbaker to supplement and stabilize natural flows.

River withdrawals for irrigation and municipal water use in Alberta have resulted in significantly reduced annual water flows of the South Saskatchewan River into Saskatchewan compared with annual flows that would have occurred without human intervention in the river's watershed in Alberta (Figure 27). Natural flows are calculated by Alberta Environment and recorded flows are measured by the Water Survey of Canada. The differences are due to water consumption and are most pronounced in dry periods but have been growing steadily since 1970. Note that in drought years (1988, 2001) consumption was 42% of the natural flow and that consumption has not been smaller than 10% of natural flow since a wet period in the early 1990s.

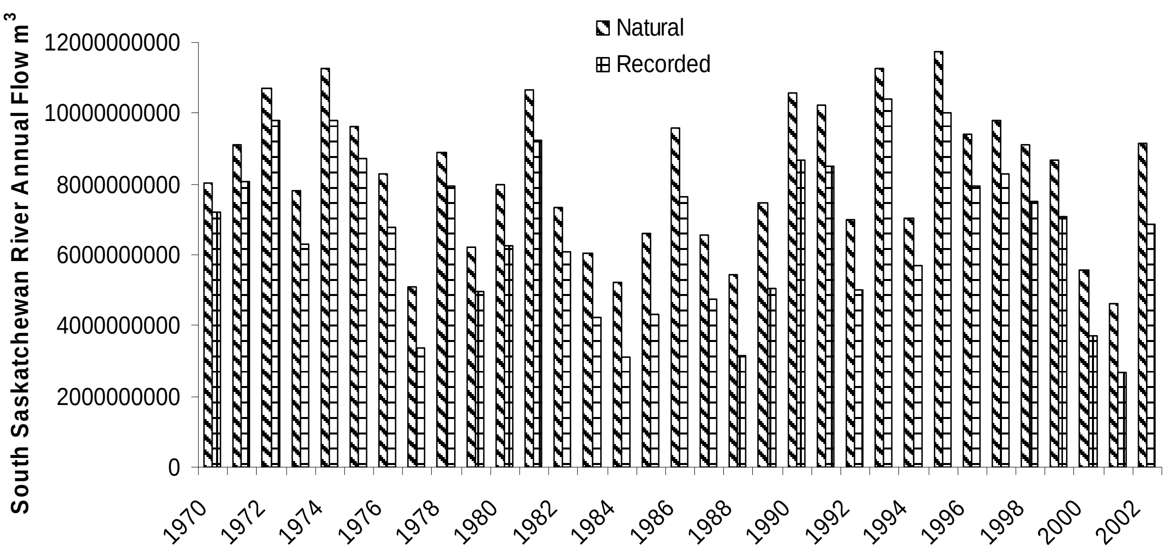


Figure 27: Impact of Upstream Water Consumption on South Saskatchewan River Annual Flows (after Pomeroy *et al*. 2007).

Current water resource management in Saskatchewan

Water resources in Saskatchewan are managed at small scales via agricultural land management on farms, resulting in impacts on soil moisture, streamflow and wetland storage regimes, and at large scales through river diversions, irrigation and water supply pipelines. The water resources of the province have been developed and managed by farmers since the time of first agricultural settlement. Cereal grain growing in most of the province requires about 125 mm soil water reserves to ensure germination and an additional 175 mm of spring rainfall is needed for an adequate crop. Where soils have adequate nutrient status or fertilization, there is roughly a 300 kg/ha increase in wheat yield for each extra 25 mm of water added by early to mid summer rainfalls. Given that most of the prairie region of Saskatchewan receives only 300 to 400 mm per year of precipitation on average, this water is just enough to adequate cereal grain growth, but there is little in excess for streamflow, wetland or groundwater recharge. The efforts of the PFRA and other agricultural agencies since the 1930s have led to substantial increases in dryland agriculture water use efficiency; as a result there are better grain yields in times of drought, more stable surface supplies for livestock, and less runoff from cultivated land. Care must be taken so that land management practices that preserve water for crop use do not result in the drying out of small streams, sloughs and wetlands that are important for wildlife, aesthetics, groundwater recharge and small scale water supplies. There is evidence that surface water supplies are dwindling in much of the cultivated portions of the province and hydrological simulations suggest a decrease in the annual flow of small streams in the southern prairies of around 25% with conversion of traditional summer-fallow lands to continuous cropping systems (Fig 28).

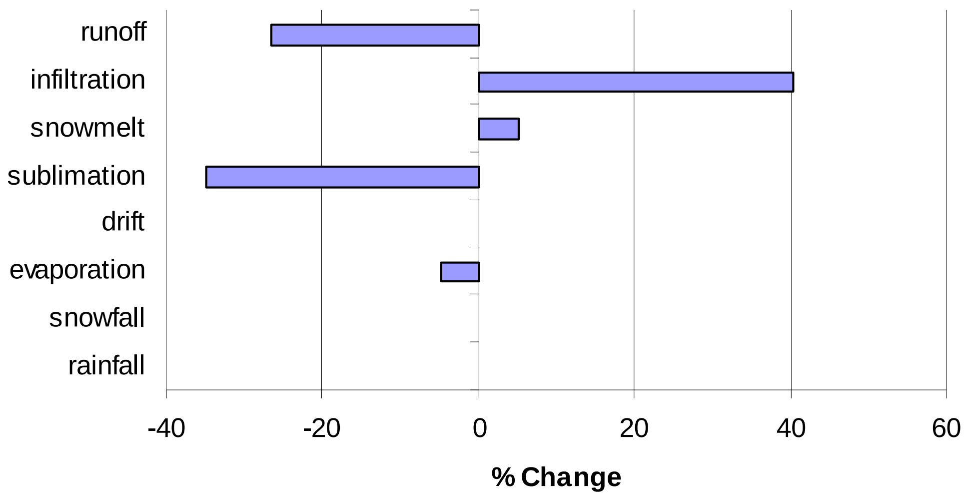


Figure 28. Percent change in water balance components by replacing 30% summer fallow coverage with continuous cropping/stubble at Creighton Tributary, southwest Saskatchewan, 1973-74 using the CRHM Model (Pomeroy *et al.* 2007).

Most of Saskatchewan's water use is in the south, whilst most of the water is in the north of the province. Much of the provincial population is now located in several large centres which require secure, high quality and steadily increasing municipal supplies; these centres also produce waste water that must be treated. Drought in the south has shown that many local surface water supplies are unreliable and alternatives are being increasingly explored. The major water resource of the south is the South Saskatchewan River which has been substantially developed as a water resource.

Gardiner Dam on the South Saskatchewan River Project and a smaller dam across the Qu'Appelle River valley were completed in 1967 and resulted in the formation of Lake Diefenbaker. Currently, about 70% of the population of Saskatchewan, including Saskatoon, Regina and Moose Jaw, receive their drinking water from Lake Diefenbaker and the South Saskatchewan River. In addition, Lake Diefenbaker provides water for irrigation, industrial use, and recreation and exerts some flood control on the downstream flow of the South Saskatchewan River. Smaller municipal water users include the towns of Hanley, Guernsey, Humboldt and Lanigan and the rural municipality of Dundurn via canal and pipeline systems. The Qu'Appelle

River system is managed for a variety of purposes by a series of control structures and inflows from Lake Diefenbaker.

Other rivers have been developed in Saskatchewan, the primary example being the Rafferty-Alameda project on the Souris River. This project was built to address problems resulting from the cycles of drought and flooding and provides a long-term water supply for the Shand power station and other users, recreational benefits and flood protection. River flow during the proposal, environmental impact assessment, and construction stages was low due to a severe drought in the late 1980s, and consequently the flood protection benefits of the project were not directly obvious. High flows in 1994, 1996 and 1997, however, caused both reservoirs to be filled by the end of the 1997 spring season - much faster than anticipated. Clearly all of these water resource projects were developed to compensate for unreliable and often insufficient water supplies and to cope with a wide range of hydrological inputs due to the already extremely variable Saskatchewan climate.

Climate Change for Saskatchewan Water Resources

No assessment of water resource impacts from climate change is possible without a thorough analysis of climate change scenarios. These scenarios not only depend on the mathematical representation of the physics of atmospheric circulation, atmospheric chemistry, water cycling, land atmosphere interaction and solar forcing, but depend on the greenhouse gas emission scenarios which ultimately depend on political, policy and economic drivers. Greenhouse gas emissions scenarios range from optimistic to balanced to pessimistic (see Climate Scenarios). As such while there is certainty in the general trends (some warming is now inevitable) there is uncertainty in the regional details of the degree of change in temperature and precipitation for future climates from these scenarios. Unfortunately, there is great uncertainty in predictive variables that are important to hydrology such as intensity of precipitation, phase of precipitation, net radiation and the duration of wet and dry periods. As well there are no reliable direct hydrological or water resource predictions from GCMs as their spatial scale is too coarse for hydrological calculations and so their outputs must be downscaled to be used.

While the climate scenarios presented in this report represent the most current information on future climate change in Saskatchewan, the assessment of impacts reported here is primarily a review of current knowledge based on published research. Therefore the climate impact studies that we review were based on prior scenarios of future climate, although they are generally similar to those developed for this assessment report. Several previous studies evaluated climate change scenarios for the larger region that includes Saskatchewan (Schindler and Donahue 2006, IPCC 2007, Sauchyn and Kulshreshtha 2008, Toyra *et al*. 2005). The IPCC North American Regional Predictions using the A1B 'balanced scenario' are of great interest because of the number of models used as an ensemble to generate a synthesized climate change projection and because they are generally accepted by policy makers. These simulations compare the difference between the 2080-2089 climate and the 1980-1989 climates. Of particular interest are temperature and precipitation responses including the annual, winter (December-January-February) and summer (June-July-August) specific responses. They suggest an annual warming of about 3.0^{o} to 3.5^{o} C and annual wetting of 5% to 10% over the province with the greatest warming and wetting in the North (Figure 29). For winter, a 3.5^{o} to 4.0^{o} C warming and a 10% to

15% wetting are projected, while for summer, a 3.0^{o} to 3.5^{o} C warming and from no change to a 5% wetting are predicted – in all cases the largest increases in the north of the province. So in general there is an annual warming and a wetting anticipated with the greatest degree of change in winter and in the north of Saskatchewan. These scenarios are in close agreement with those in the Scenarios of Future Climate section above from Barrow (2009). Sauchyn and Kulshreshtha (2008) discuss these projections in much greater detail and include a range of scenario assumptions and models – their results are consistent in direction and magnitude with the IPCC in general though there is of course a much greater range and detail available. The range of predictions shown by Sauchyn (2007) is important in quantifying uncertainty for hydrological predictions – some scenarios showed drying occurring in the summer and most did not show significant summer wetting.

Barrow and Yu (2005) assessed detailed climate scenarios for Alberta, from which the Saskatchewan River system receives most of its runoff. In Alberta, changes in annual mean temperature by the 2050s are typically between 3°C and 5°C. For the 2050s, changes in annual precipitation are generally within the range –10% to +15%, and any decreases in annual precipitation are generally driven by decreases in summer precipitation. By the 2080s, however, all climate change scenarios indicate increases in annual precipitation of up to 15%. These are roughly consistent with the IPCC and Sauchyn assessments for Saskatchewan though mid-century drier conditions are possible for south-western Alberta.

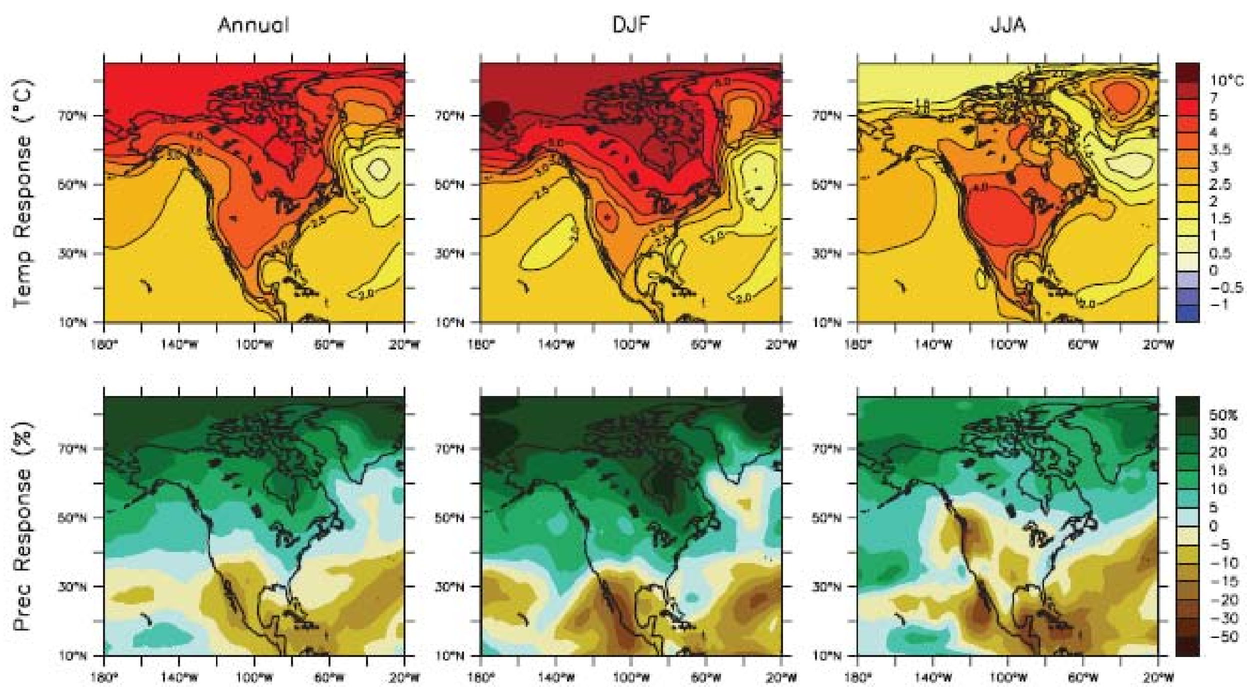


Figure 29. North American Regional Predictions from the IPCC (2007), difference between the 2080-2089 climate and the 1980-1989 climates.

Toyra *et al*. (2005) evaluated GCM output for current climate against gridded observations in order to select the most reliable climate model for use in generating scenarios for water resource predictions in the Prairies. They evaluated 11 GCM outputs and selected three as having the most reliable outputs for assessing future climate (Table 1). These models were then used to estimate the 2050 and 2080 climates under two different emission scenarios. Whilst there is a wide range in results, the median of the results suggest a wetting and warming consistent with the IPCC. Because these models were evaluated against gridded data there is somewhat greater confidence in the future climate results than for simple ensembles of all models which include those which could not predict current climate accurately. For this reason, these scenarios were used to drive the water resource predictions presented in the next section for the South Saskatchewan River (Pietroniro *et al*., unpublished) and for Creighton Tributary of Bad Lake Research Basin in southwestern Saskatchewan (Fang and Pomeroy 2008).

Table 1. The range of mean temperature and total precipitation change for the 2050 and 2080 centred timelines as predicted by ECHAM4, HadCM3 and NCAR-PCM based on the SRES A2 and B2 emission scenarios. The median change based on the three GCMs is also provided as a reference. The values represent change in relation to the 1961-1990 climatology. From Toyra *et al*. (2005).

	2050		2080	
	Range	Median	Range	Median
Precipitation (%)				
Annual	0.4-12.7	9.5	0.9-20.0	14.2
Winter	7.1-20.0	11.0	7.7-37.5	15.5
Spring	-1.6-20.7	7.5	-3.1-25.4	13.5
Summer	-11.0-8.4	0.5	-11.7-9.9	3.9
Autumn	4.0-16.7	9.1	-0.1-30.9	15.4
Temperature (°C)				
Annual	1.8-3.6	2.0	2.5-5.5	3.8
Winter	0.7-5.7	2.6	2.2-7.4	4.7
Spring	0.9-2.3	1.6	1.8-4.3	2.9
Summer	1.5-3.2	2.9	1.8-5.6	3.9
Autumn	1.6-3.2	2.5	2.1-5.2	3.8

Water Resources under Climate Change for Saskatchewan

There is a dearth of rigorous studies that couple downscaled GCM outputs to physically based hydrological models for Saskatchewan. Studies such as Schindler and Donahue (2006) use overly simplistic potential evaporation calculations and do not estimate the basin scale hydrological response to climate change scenario products. The only studies found that addressed this for Saskatchewan are an incompletely published body of research led by Dr. Alain Pietroniro of Environment Canada for the South Saskatchewan River Basin Study and a short partly published simulation by Xing Fang and John Pomeroy of the University of Saskatchewan for a small representative basin in south-western Saskatchewan.

South Saskatchewan River Basin study and subsequent analysis

The purpose of the South Saskatchewan River Basin Study (SSRB) was to identify the risks and the challenges facing the human and aquatic communities in the South Saskatchewan River Basin (SSRB) that derive from anticipated climate change and economic growth. The study was led by Dr. Alain Pietroniro of Environment Canada and is briefly described in the SSRB Report (Martz *et al*. 2007). The two driving factors considered were:

1) the hydrological impacts of climate change that might occur for the SSRB as a whole and for the individual sub-basins within the SSRB. Changes in temperature, precipitation, and evapotranspiration are all variables that affect these impacts.
2) expansion in human activities that create demand for water resources.

Focussing on the hydrological impacts of climate change the hydrology of the SSRB was modelled and calibrated to the normal period 1961-1990 using the WATFLOOD model. WATFLOOD is a conceptual hydrological model that was adapted and calibrated to naturalized flows of the SSR. It was then run for future GCM climatology as recommended by Toyra *et al*. (2005) for the IPCC (1999) A2, B2 scenarios with the three most reliable GCMs. This provided six scenario outputs from the model. The normal period produced reliable model outputs upstream of Lake Diefenbaker (but less so downstream) and so the flows into Lake Diefenbaker are the subject of the analysis here. The basin, and nodes and sub-nodes of the SSRB modelling exercise with streamflow changes as a percent of normal for the various scenarios and models are shown in Figure 30. It is seen that for the South Saskatchewan River entering Lake Diefenbaker the flow, as estimated from the mean of all model outputs, is expected to decrease by 8.5% with a range in this estimate from an increase of 8% in flow in the wettest scenario to a decrease of 22% in flow for the driest scenario. Further breakdowns of these results by sub-basin provides the basin water supply and this analysis suggests that under all scenarios there is a negligible to modest increase in local water supply over the (mainly) Saskatchewan portion of the lower SSRB with an average increase of 8% with a range from nought to 14%. This modest increase in the lower SSRB does not compensate for the decreases in the upper SSRB which results in the generally lower river flows entering Saskatchewan and being passed on to Saskatoon.

Climate change can alter water resources within the SSRB and make current water practices unsustainable from an ecological perspective. The current data and projections however, do not predict ecological collapse, nor do they say that current projections in economic and population growth are unstable. If on the other hand, current human consumption is close to ecological limits, then climate change can make current consumption unstable. With this in mind, if consumption does not change to accommodate the potential fall in water supplies, then extreme water stresses may transpire along with a potential ecological collapse within the SSRB.

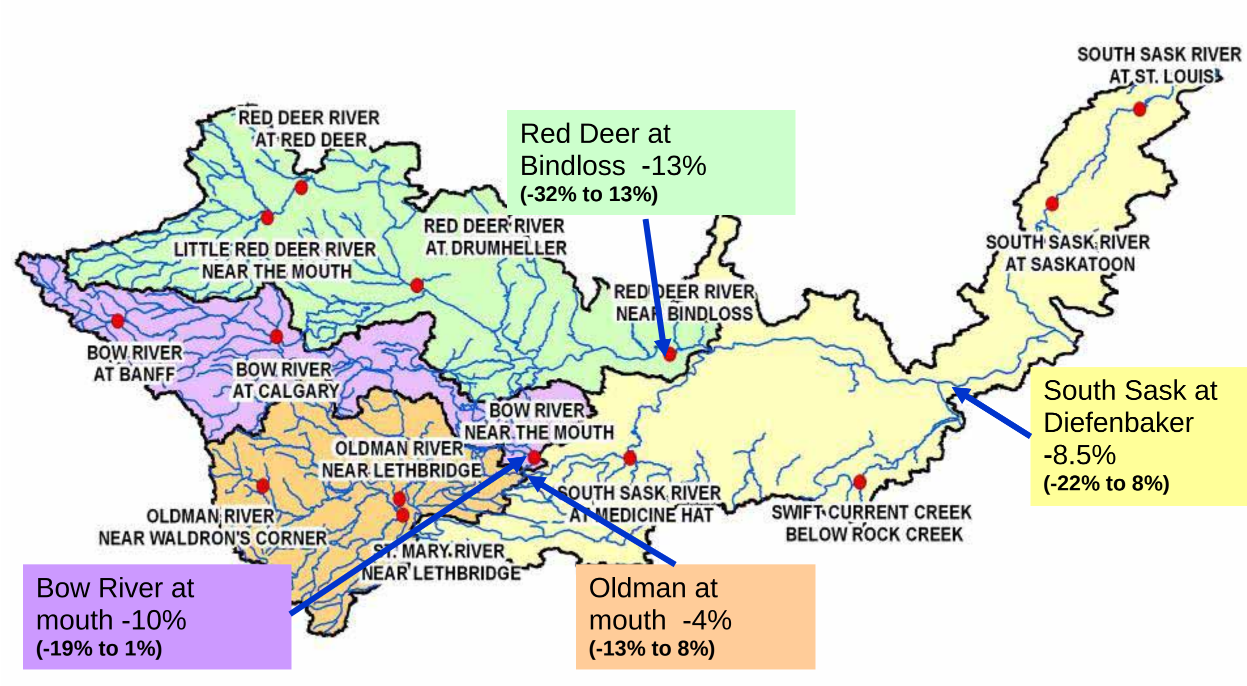


Figure 30. South Saskatchewan River Basin and SSRB Study Model nodes along with mean and range of change in annual streamflow for individual sub-basins. Changes for the normal period 1961-1990 to future period 2039-2070 as a percentage of naturalized annual flows in normal period (from Al Pietroniro and Bruneau and Toth 2007).

These modelled changes in future flows need to be taken in the context of recorded changes in flow and changes in the estimated naturalized flow for the SSR entering Lake Diefenbaker (Figure 8). Analysis of flow records and naturalized flow calculations from Alberta Environment shows that naturalized flows have declined by approximately 1.2 billion m^3 over 90 years (-12%), and actual flows have declined by about 4 billion m^3 over 90 years (-40%). The 12% decline in naturalized flows from 1912 to 2002 can be primarily attributed to climate change, though it may be partly impacted by land use change (afforestation), changes in measurement technology and errors in the naturalized flow calculation. Of the 40% decline in actual flows from 1912 to 2002, 70% of this decline is due to upstream water consumption, and 30% is due to hydrological change in the naturalized flows. The modelled change in future flow due to future climate change is -546 million m^3 which would mean a reduction since 1912 of 1.7 billion m^3 over about 150 years. So the climate model scenario results suggest a smaller reduction in naturalized river discharge due to future climate change to the mid-21st C than has already occurred in the 20th C. In all cases the decline in river flow due to upstream consumption far exceeds the decline due to climate change and other hydrological factors. This suggests that modification of upstream consumption patterns through water management could completely compensate for the changes in SSR streamflow from that measured in the early 20th C due to existing and future climate changes.

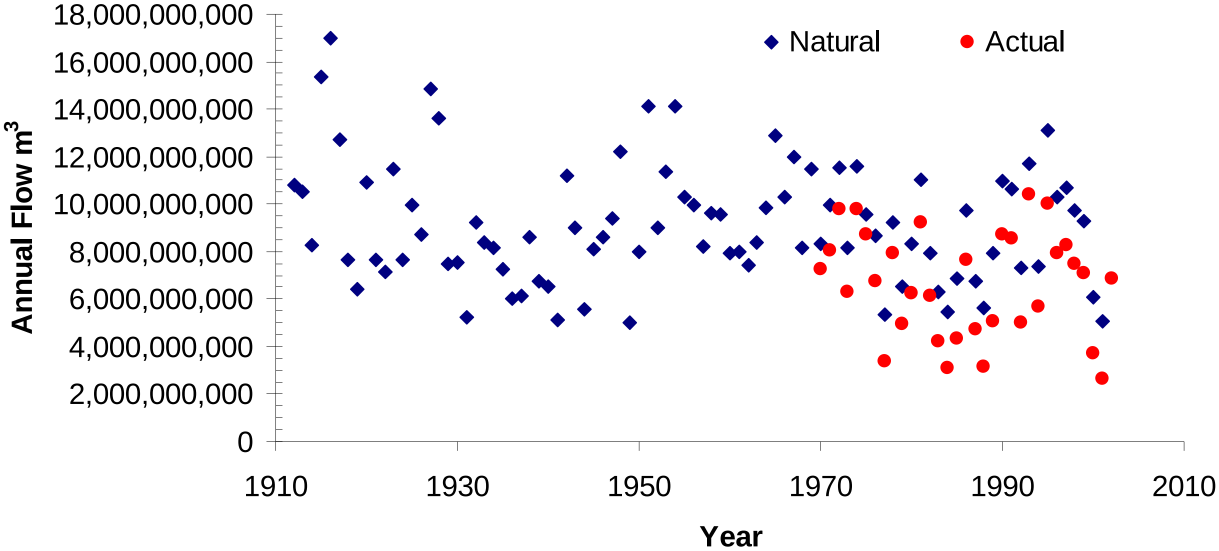


Figure 31. Naturalized and actual annual flows of the South Saskatchewan River entering Lake Diefenbaker. Naturalized flows are estimates with all water consumption "returned" to the streamflow, actual flows are measured and included consumption losses.

Representative prairie basin analysis

Toyra *et al*. (2005) from a review of several general circulation model simulations for the mid 21st century suggested that a warmer and 'wetter' climate is most likely for the middle and latter part of this century. The median of three most reliable scenarios (ECHAM4, HadCM3 and NCAR-PCM) suggests a rise in annual winter temperature and precipitation from the 1961-1990 average of 2.6 ºC and 11.0% by 2050, and to 4.7 ºC and 15.5% by 2080. These changes to climate were modelled for spring runoff at the Bad Lake Research Basin by perturbing the 1974-1975 hourly meteorology by the percentages described above and then recalculating the phase of precipitation, snowfall, blowing snow, snowmelt, infiltration to frozen soils and snowmelt runoff for Creighton Tributary of Bad Lake by Fang and Pomeroy (2007) using the Cold Regions Hydrological Model platform, CRHM (Pomeroy *et al*. 2007).

CRHM is based on a modular, object-oriented structure in which component modules represent basin descriptions, observations, or physically-based algorithms for calculating hydrological processes. A full description of CRHM is provided by Pomeroy *et al.* (2007). CRHM permits the assembly of a purposely built model from a library of processes, and interfaces the model to the basin based on a user-selected spatial resolution. Hydrological processes such as wind redistribution of snow, snowmelt, snowmelt infiltration into frozen soils, and evaporation are common in Prairie winter and early spring. These processes all influence spring snowmelt runoff. Snow accumulation (often call snow water equivalent, or SWE) controls the amount of available snow for melting and is affected by wind in open prairie environments. Blowing snow in open environments can erode and sublimate or redistribute as much as 75% of annual snowfall from open, exposed fallow fields in southern Saskatchewan (Pomeroy and Gray 1995). Redistribution is from open, well exposed surfaces to sheltered vegetated surfaces. The amount of surface snowmelt runoff is governed by both snowmelt infiltration and SWE. Snowmelt infiltration reduces the direct surface runoff, decreasing amount of peak flows (Norum *et al.* 76).

Relevant modules chosen using CRHM for these simulations included the Prairie Blowing Snow Model (Pomeroy and Li 2000), the Energy-Budget Snowmelt Model (Gray and Landine 1988), Gray's expression for snowmelt infiltration (Gray *et al.* 1985), Granger's evaporation expression for estimating actual evaporation from unsaturated surface (Granger and Gray 1989, Granger and Pomeroy 1997), a soil moisture balance model for calculating soil moisture balance and drainage (Leavesley *et al.* 1983), and Clark's lag and route runoff timing estimation procedure (Clark 1945). These modules were assembled along with modules for radiation estimation and albedo changes (Garnier and Ohmura 1970, Granger and Gray 1990, Gray and Landine 1987) into CRHM. This enabled the estimation of SWE after wind redistribution, snowmelt rate, cumulative snowmelt, cumulative snowmelt infiltration into unsaturated frozen soils (INF), and actual evaporation (E). Actual evaporation is that calculated using the method of Granger and Pomeroy (1997) which is entirely an atmospheric energy balance and feedback approach, the approach is then modified by CRHM in that actual evaporation (E) is limited by a surface mass balance; when interception storage and soil moisture reserves are depleted evaporation cannot proceed. Snowmelt runoff over the event (R) was estimated based on a simplified conservation equation:

$$R = SWE - INF - E \quad (1)$$

where all terms are in mm of water equivalent.

Calculations in CRHM are made on hydrological response units (HRU). Based on the major land uses in the basin and on physiography, three HRU (fallow field, stubble field, and grassland [coulee]) were chosen for the snowmelt runoff simulation. The total snowmelt runoff from these HRU provided the cumulative basin snowmelt runoff as:

$$R_{basin} = R_{fallow}\frac{Area_{fallow}}{Area_{basin}} + R_{stubble}\frac{Area_{stubble}}{Area_{basin}} + R_{grassland}\frac{Area_{grassland}}{Area_{basin}} \quad (2)$$

where R_{basin}, R_{fallow}, $R_{stubble}$, and $R_{grassland}$ are basin snowmelt runoff, snowmelt runoff over fallow field, stubble field, and grassland, respectively; $Area_{basin}$, $Area_{fallow}$, $Area_{stubble}$, and $Area_{grassland}$ are area of basin, fallow field, stubble field, and grassland, respectively. The definition of several HRU within a basin permits consideration of effects due to variable contributing area – HRU are only part of the contributing area for streamflow when they produce infiltration excess or surface runoff.

Using Toyra at al.'s (2005) median scenario with the CHRM for the *et al*Bad Lake Research Basin resulted in a 24% increase and then a 37% decrease in cumulative runoff in the years 2050 and 2080, respectively, compared to the basin runoff (54 mm) in spring of 1975 (Figure 32). Runoff in 1975 started around 18 March, but by 2050 it is predicted to start around 22 February and by 20 February in 2080. The increased prairie spring runoff under moderate climate warming (2050) shows that increased winter precipitation is more important than increased winter temperatures in spring runoff generation processes. This model result counters commonly held assumptions that climate warming must lead to drier conditions (Schindler and Donahue

2006) and the implicit assumption that temperature increases would overwhelm increases in precipitation in their effect on hydrology under a warming climate. However by 2080 the spring runoff has decreased substantially, showing that as climate change progresses, there is some thresholding behaviour causing the initial increase in streamflows to rapidly diminish.

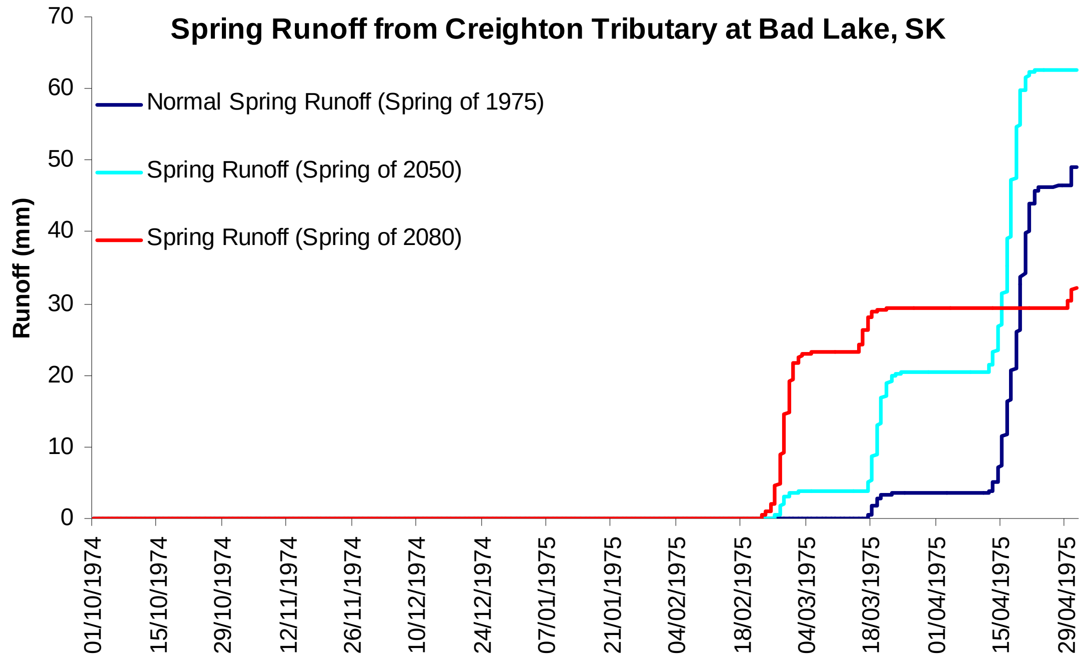


Figure 32. Spring runoff from Creighton Tributary, SW Saskatchewan as modelled by CRHM under 1974-1975 climate and then using the average Toyra *et al*. (2005) climate scenarios pertubations for 2050 and 2080.

Winter snowpack evolution is shown in Figure 33 for 1974-1975 and the 2050 and 2080 mean scenarios. It is seen that for the 2049-2050 winter there is little change in snow accumulation until late winter and a continuous snowpack is retained until mid April. Suppression of blowing snow sublimation by the warmer winter has partially offset the reduced snowfall due to increased rainfall. The increased runoff in this simulation is due to mid-winter melts causing an ice layer to form on top of the frozen soil and hence restricting spring infiltration and increasing the runoff ratio dramatically. However by 2079-2080 there is no longer a continuous snow-covered period in winter and the snowpack completely ablates in March with most melt occurring in February. The longer, slower mid-winter melt permits infiltration of the reduced snowpack and relatively little runoff. These results are very preliminary and further study of the climate change impact on prairie runoff using physically based models such as CRHM is clearly needed.

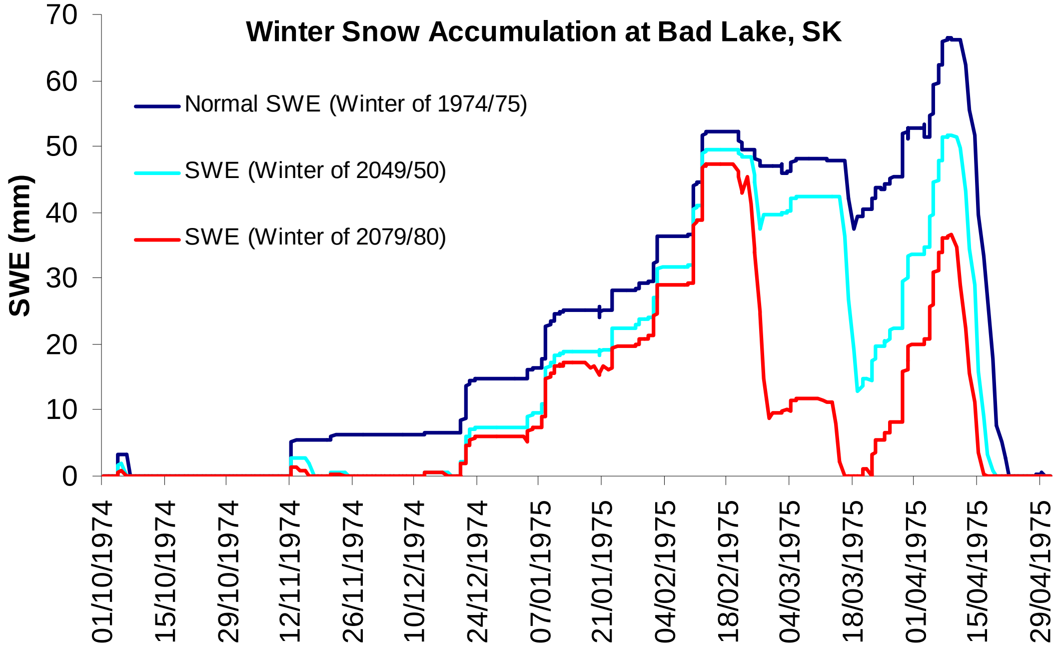


Figure 33. Winter snowpack accumulation at Creighton Tributary, SW Saskatchewan for 1974-1975 and under mean Toyra *et al*. climate scenarios for 2049-2050 and 2079-2080.

Options for Adaptation of Future Water Resources Management Practises, Policies and Infrastructure

The preceding modelling results, while provisional, suggest there may not be dramatic decline in annual runoff in the prairies under climate change and that streamflow will increase in the near-term for certain scenarios and under moderate degrees of climate change. This is because much of the predicted warming and wetting occurs during winter and snowmelt is the primary mechanism for generation of streamflow in both the Saskatchewan River system and for local prairie streams.

What these studies do not address is the longer summer periods and longer period for evapotranspiration will result in drier soils for a longer period in the summer, even without higher actual evapotranspiration rates as suggested by Fernandes *et al*., (2009). So while river and streamflows might be reduced by small amounts or even increase, water needs for agriculture will likely increase and so pressure for irrigation of farmland using river water will increase. These studies also do not address the potentially increasing year-to-year variability, for example drought years, where pressure on water resources from increased demand and diminished supply will likely cause a crisis in future years.

In all cases the uncertainties in the model outputs and driving hydrometeorological data for current simulations make recommending adaptation measures very difficult as the range of predictions is from a decrease to an increase in available streamflow compared to current estimates. So it is imperative that the scientific basis of these models be improved so that there is reduced uncertainty in model predictions. The models also need to be carefully verified with observations from research basins and test bed regions. The current climate and water resources available in the headwater basins in the mountains and prairies are themselves uncertain and need to be better quantified to permit comparisons of future climate and water resource predictions with the current situation.

Adaptation for South Saskatchewan River water resources

The anticipated declines in future annual streamflow on the South Saskatchewan River entering Saskatchewan of 8.5% (+8% to -22%) can be compensated for (if necessary at all) by decreasing water consumption upstream. Martz *et al*. (2007) note that the share of surface water used in the SSRB for agriculture is 86.5%, with only 8.7% going to municipal use, 3% for thermal and 1.8% for industrial use. It is clear that more efficient water use for irrigation or a reduction in irrigated acreage in Alberta could compensate for the reduced water availability, which is due mainly to reduced mountain snowmelt. Saskatchewan should evaluate its plans for increased irrigation very carefully in light of reduced water availability from Alberta due to consumption and climate change.

Uncertainties in the above analysis relate to drought years when irrigation demand is highest, runoff will be lowest and lack of options to manage water resources by reduced irrigation acreage in Alberta could result in magnified economic damage, in excess of that due to the reduction in precipitation in the drought itself. It is unlikely that even stringent urban water conservation measures alone could make up for the reduced flows in such years. The recent prairie drought was multi-year (Stewart *et al*. 2008); even a large reservoir such as Lake Diefenbaker cannot sustain higher outputs than inputs for periods of several years. So it is possible in drought years that unless Alberta acted to reduce irrigation demand, streamflows downstream of Lake Diefenbaker could be negatively affected to a degree not experienced since the dam was constructed. This would have direct impact on ecological instream flow needs and water supplies for Saskatoon, Regina and Moose Jaw in addition to smaller centres. Further research is needed to explore the possibilities of low flows under these scenarios and whether the "patchy" spatial distribution of many droughts would permit water supplies in the North Saskatchewan River to compensate for reduced flow from the South Saskatchewan River downstream of the confluence.

Integrated basin management of the South Saskatchewan River across both Alberta and Saskatchewan is the preferred management method for dealing with these uncertainties in cross border situations. Integrated basin management is very successful in Europe where it is implemented in the Water Framework Directive. Since 50% of a very small naturalized flow may be insufficient for future Saskatchewan water uses, the Prairie Provinces Water Apportionment Agreement might need to be revisited in terms of absolute minimums, low flows and implementation of integrated basin management with actual apportionment powers.

Adaptation for Saskatchewan prairie water resources

For small prairie streams the main economic water use is the water that does not run off, but infiltrates soils and then can be used for crop and pasture growth. Farmers are currently very successful at retaining this water on the field through continuous cropping to reduce blowing snow sublimation and minimum tillage to promote infiltration into frozen soils through natural macropores (Figure 28). These methods likely ameliorated impacts on agricultural production in the last drought compared to what might have been with the former fallow-stubble rotation and frequent tillage methods, and will prove resilient under the increases and decreases in prairie water supply due to climate change. However, the increased efficiency of agricultural water management currently leaves little water for replenishing sloughs and wetlands and recharging groundwater (Hayashi *et al*. 2003). Under moderate climate change (*e.g.* 2050) there may be an increase in small stream flows for many parts of the province, but as climate change progresses later in the century there may be dramatic drops in runoff and the flow of small streams to wetlands and depressions and to small prairie rivers. Infrastructure in roads, culverts, dugouts and reservoirs will have difficulty keeping up with this rapid change. Wetlands might initially increase and then ultimately decrease causing large fluctuations in waterfowl populations, difficulty in specifying sustainable yield from groundwater supplies as recharge changes and difficulties in maintaining suitable levels for recreational lakes and reservoirs such as Fishing Lake and Rafferty-Alameda. Since the impacts of late-century climate change on Saskatchewan agricultural practises are uncertain (winter wheat or even corn and soy beans may be possible) there is time and opportunity to design new crop varieties and tillage methods to leave some water for runoff to natural ecosystems.

The co-incidence of increased wetland drainage and climate change to a wetter and warmer winter might be already increasing streamflow from small watersheds in the eastern part of the province and this might increase dramatically if drainage and the initial scenario results from Figure 32 continue as expected. Figure 34 shows annual streamflow for Smith Creek in eastern Saskatchewan. The five peak years for streamflow are all since 1995. Reduced drainage of wetlands could compensate for this increase in streamflow (Pomeroy *et al*. 2008) but the effectiveness of reducing drainage and exactly which wetlands are important to retain intact in a streamflow network are still unknown. The current tendency to drain wetlands along with climate change impacts will result in reduced water storage for waterfowl and groundwater recharge as well as in increased streamflow.

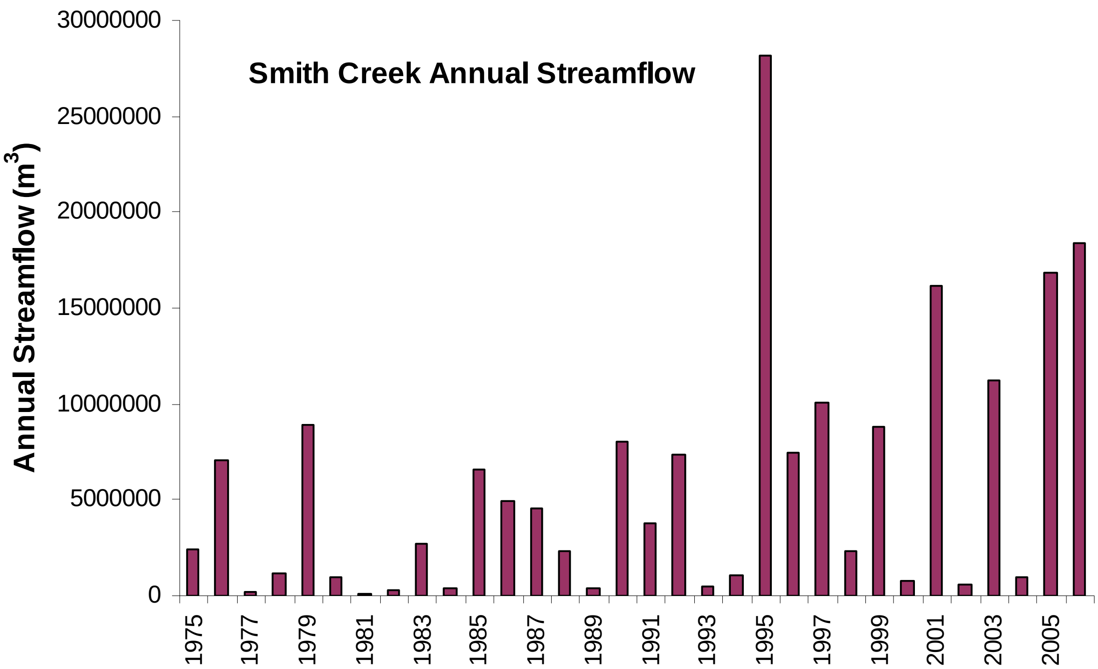


Figure 34. Annual measured streamflow for Smith Creek near Langenberg, Sask., 1975-2006.

Incentive programs would be necessary to make these agricultural management techniques desirable for producers. Not only drainage exacerbates the drying of wetlands. Ironically, conservation tillage and conversion to grassland will likely exacerbate drying of wetlands – direct evidence of this is apparent from studies at St Denis in the prairie pothole region east of Saskatoon (van der Kamp *et al*. 2003); the effects of land use on this drying of wetlands are most pronounced during drought but can be ameliorated by reducing grassland coverage (Fang and Pomeroy 2008). Physically based hydrological models such as CRHM run with carefully downscaled GCM scenario results could be used to develop hypothetical land management scenarios and predict how these might ameliorate the impacts of climate change on prairie soil, stream, wetland and groundwater water resources. Implementation of land management systems is best assessed at the watershed level, perhaps by implementing integrated watershed plans with enforceable land use controls and incentives at the watershed authority level in Saskatchewan, so that techniques could be tailored to the local climate change and watershed drainage characteristics. Experience has shown that economic incentives, regulations and enforcement are superior to best management practices in promoting land use changes. If land use changes cannot be effected then extensive infrastructure redesign for increased culvert size, changed road allowances, bridge redesign, beach resort location and town sewerage and drainage systems may be necessary.

Conclusions

Prairie province hydrology is dominated by cold regions processes so that snowmelt is the primary hydrological event of the year for both the major rivers that derive from the Rocky Mountains and small streams and rivers that arise in Saskatchewan. Climate change impacts on water resources are therefore focussed on changes to snow accumulation, snowmelt and infiltration to frozen soils. Climate change scenarios suggest generally warmer and wetter winters for Saskatchewan. Large scale hydrological models that take these scenarios into account have suggested changes in the annual streamflow of the South Saskatchewan River ranging from an 8% increase to a 22% decrease, with an 8.5% decrease being an average prediction. Small scale hydrological models for prairie streams suggest a 24% increase in spring runoff by 2050 followed by a 37% decrease by 2080 is possible as the winter snowcover becomes discontinuous. Both model results suggest that there is not a dramatic drying of the prairies to be anticipated under climate change and that in some cases streamflow will increase for certain scenarios and under moderate degrees of climate change.

What these modelling results cannot yet address is that the longer summer periods and longer period for evapotranspiration will result in drier soils for a longer period in the summer, even without higher actual evapotranspiration rates as suggested by Fernandes *et al*., (2009). So while river and streamflows might be reduced by small amounts or even increase, water needs for agriculture will likely increase and so pressure for irrigation of farmland using river water will increase.

For the major rivers draining from Alberta into Saskatchewan, more efficient water use for irrigation or a reduction in irrigated acreage in Alberta could compensate for the reduced water availability, which is due mainly to reduced mountain snowmelt. Current minimum tillage and continuous cropping systems are resilient for changes to agricultural water resources. However, as climate change progresses later in the 21^{st} C there will be dramatic drops in runoff and the flow of small streams to wetlands and depressions and to small prairie rivers. This could result in the loss of waterfowl from the prairie pothole region, unsustainable groundwater supplies with reduced recharge and difficulties in maintaining recreational lakes and reservoirs. Since the impacts of late-century climate change on Saskatchewan agricultural practises are uncertain (winter wheat or even corn and soy beans may be possible) there is time and opportunity to design new crop varieties and tillage methods to leave some water for runoff to natural ecosystems.

Integrated basin management of the South Saskatchewan River across both Alberta and Saskatchewan and for smaller watersheds in Saskatchewan is the preferred adaptation method for dealing with these uncertainties. The Prairie Provinces Water Apportionment Agreement and various conservation and development acts might need to be revisited so that they can be used to implement integrated basin management plans with apportionment powers, enforceable land use controls and agricultural management incentives.

In all cases the uncertainties in the model outputs and driving hydrometeorological data for current simulations make recommending adaptation measures very difficult as the range of predictions is from a decrease to an increase in available streamflow compared to current estimates. It is imperative that the scientific basis of these hydrological models be improved so that there is reduced uncertainty in model predictions. The models also need to be carefully verified with observations from research basins and test bed regions in the prairies and mountains. The current climate and water resources available in the headwater basins are themselves uncertain and need to be better quantified to permit comparisons of future climate and water resource predictions with the current situation.

ECOSYSTEMS

Introduction

In a global analysis, climate change is rated as second only to land use in importance as a factor that is expected to determine changes in biodiversity over the current century (Sala *et al*. 2000). In Saskatchewan's case, given relatively low population density and relatively stable land use, climate change may in fact exceed land use change as the dominant biodiversity and ecosystems change factor. This will be particularly so in northern Saskatchewan, the part of the province least actively managed and with the lowest population density.

Changes in climate will alter environmental conditions to the benefit of some species, and detriment of others, often with economic consequences. For example, as vegetation and animals shift in response to changing climate, tourism and recreation activities such as fishing and bird watching will be affected, and agricultural, forestry and urban pest management practices will have to adjust.

Biodiversity and Productivity

In the absence of moisture limitations or other constraints, plant productivity should rise with an increase in growing season length and temperature. Increased photosynthetic activity for much of Canada over the period 1981-91 has been attributed to a longer growing season (Myneni *et al*. 1997). However, the most recent climate change scenarios for Saskatchewan indicate that the Province is most likely to become drier on an annual basis, and most especially so during the growing season (Barrow 2009). This increasing aridity is the single most important ecosystem impact and also represents a major biodiversity management challenge.

There is a possibility that one climate change factor, increasing atmospheric CO_2 concentrations, could lessen the aridity effect on terrestrial ecosystems. Increasing atmospheric CO_2 concentrations have a fertilisation effect which increases the water use efficiency of some plant species (Lemon 1983, Long *et al*. 2004), although there are many uncertainties about the sum effect (Wheaton 1997). Wang *et al*. (2006) reported a positive CO_2 enrichment effect on the growth of white spruce in south-western Manitoba. Johnston and Williamson (2005), with reference to the Saskatchewan boreal forest, found that even under drought conditions the CO_2 enrichment effect could result in an increase in productivity. On the other hand, modelling and an empirical study by Gracia *et al*. (2001) suggested that any positive CO_2 fertilisation effect is neutralised amongst evergreens, because growth is constrained by moisture limitations.

Prediction of overall changes in forest CO_2 uptake and storage, independent of inter-species variations, is not yet possible (Gitay *et al*. 2001). One major problem in predicting CO_2 enrichment impacts on a specific species is that the impact occurs on all vegetation simultaneously. It is not enough to know the CO_2 response of one species, rather one needs to know the relative growth advantage, if any, gained by all vegetation species competing for resources at a given site. In their metastudy Boisvenue and Running (2006) concluded "there is no clear answer as to whether rising CO_2 concentrations will cause forests to grow faster and store more carbon".

Increasing CO_2 concentrations could also affect the species composition of grasslands. Theoretically, CO_2 fertilisation provides a greater relative benefit to C_3 grasses than to C_4 grasses (Long and Hutchin 1991, Parton *et al*. 1994, Collatz *et al.* 1998). However, ecosystem experiments have shown that under the dry conditions typical of grasslands this advantage tends to be reduced or eliminated (Nie *et al.* 1992, Wand *et al*. 1999, Campbell and Stafford Smith 2000).

Climate factors beyond moisture balance and CO_2 concentrations will also affect ecosystems. Some research suggests that climate variability is increasing (Kharin and Zwiers 2000). This means that not only is "average" climate changing, but that incidences of extreme climate events, *i.e.* deviations from average climate, may increase in frequency and duration. Such events can have major ecosystems impacts. For example, the Prairies drought of 2001-02 reduced the net production of aspen stands to near zero owing to reduced growth and increased mortality (Hogg *et al*. 2008). The prolonged Prairies droughts of the 1930s caused major changes in grassland composition – taller and more moisture-demanding species such as western porcupine grass and wheatgrasses decreased in relative abundance while shorter and more drought-tolerant species such as blue grama increased (Coupland 1959). If droughts become more frequent, or intense, resultant vegetation composition and range shifts are certainly possible.

Changes in the timing and intensity of freeze-thaw events, diurnal temperature patterns (Gitay *et al*. 2001), and storm and wind stress events may also influence vegetation distribution or survival, especially of various tree species (Macdonald *et al.* 1998), but the details of how this will occur are not known. Ultraviolet B radiation and ground-level ozone levels are increasing and expected to negatively impact vegetation, possibly nullifying any positive CO_2 enrichment effect (Henderson *et al*. 2002). Experiments at the Free Air Carbon Enrichment (FACE) site in Wisconsin (Free Air Carbon Enrichment Experiment 2009) find that the negative impacts of increasing ground level ozone nullify any carbon enrichment impact, and also that the carbon-enriched environment seems to favour pathogen attacks on trees and to weaken tree physiology.

Nitrogen deposition from industrial activity may be affecting species growth and competitive interactions, even in prairie locations far from industrial centres (Kochy and Wilson 2001). Saskatchewan may be facing increasing rates of SO_2 deposition in the northwest of the Province, owing to increasing tar sands processing in neighbouring Alberta. Environmental monitoring is just beginning to gage the extent of this issue, but it may combine with climate change impacts to negatively impact both land and water ecosystems in the affected region.

The global boreal forest has been identified as one the most climate change threatened biomes on the planet (Soja *et al.* 2007, Lenten *et al.* 2008). In a comprehensive study of the circumpolar boreal forest biome (including Saskatchewan's boreal component), Soja *et al.* (2007) concluded that evidence of significant change, including more frequent and intense fires and insect infestations, is already evident – indeed change was proceeding faster even than many model predictions. Parisien *et al.* (2005) predicted increased fire frequency and intensity in the Saskatchewan boreal forest as the result of new climate conditions. Thornley and Cannell (2004), modelling increased fire frequency in coniferous forests for the climate of Prince Albert, predicted long-term decline in net primary productivity. Hogg and Bernier (2005) suggested increasing vulnerability to drought, insects and fire in Canada's western boreal forest.

Increased average winter temperatures will lead to greater overwinter survival of pathogens and increased disease severity (Harvell *et al*. 2002). Warmer temperatures (quite apart from the possible aridity consequences from increased evapotranspiration) seem to favour an intensification of pathogen attacks on trees (van Mantgem *et al*. 2009). A great unknown for Saskatchewan is the degree to which jack pine stands in the boreal forest may be impacted by the Mountain Pine Beetle. This insect has caused enormous mortality in BC lodgepole pine forests, and is now well established in Alberta lodgepole stands. It has also now been found as far east as jack pine stands in Saskatchewan's boreal forest (Natural Resources Canada 2006).

Drought conditions weaken trees' defences to more virulent pathogens (Saporta *et al*. 1998). As conditions become more xeric, the lifespan of conifer needles is reduced, placing conifers under increasing stress (Gracia *et al*. 2002). The boreal forest is expected to be significantly affected by climate change, especially at its southern boundary (Scholze *et al*. 2006, Carr *et al*. 2004, Henderson *et al*. 2002, Herrington *et al*. 1997), where tree growth is typically moisture limited. In the northern boreal region, however, where the growth limitation is heat, productivity may well increase. Increasing aridity can be expected to impact large areas of peatlands and muskeg (with secondary impacts on peatlands-dependent species).

Vegetation Zone Response

Impact models that correlate the current distributions of ecoregions with the current climate, and then fit future projected ecosystem distributions to future climate scenarios (*e.g.*, Davis and Zabinski 1993) have projected significant changes in boreal forest area and quality. Models based on plant growth and population dynamics, *i.e.* models which show how the ecosystem evolves over time in response to ongoing climate change might yield more detailed predictions, but also require increased modelling complexity. Major changes in species representation are projected for Saskatchewan's boreal forest by 2080 through impact modelling (Carr *et al*. 2004, utilizing CGCM1 and the A1 emission scenario). Native and non-native tree species range modelling by Thorpe and Godwin (2009) under a suite of Fourth Assessment climate change scenarios suggested that native conifers will be significantly impacted by increasing aridity and decline in the southern parts of their current range, while the boreal hardwoods, in particular aspen, may prove more robust and more able to persist in their traditional ranges. Green ash and bur oak showed potential for range expansion at upland forest sites in Saskatchewan. Thorpe and Godwin (2009) suggested various tree species that may have potential for intentional plantings intended to retain forest cover as climate change advances, including the natives lodgepole and ponderosa pine, and the non-natives Scots pine and Siberian larch. Johnston (1996) noted that increased fire disturbance may favour hardwoods, such as aspen, over conifers, such as white spruce.

The northern extremes of the boreal forest will likely extend under climate warming, but the rate of this northward extension of the forest is uncertain, and will take decades as trees respond to variations in soil temperatures, permafrost and uncertain seed dispersal and establishment (Lloyd

2005). Forest expansion may occur fairly smoothly and consistently year to year at the northern forest boundary (although site factors such as soil suitability will vary along the boundary and promote heterogeneous change). A northward shift at the southern boundary of the Saskatchewan boreal forest is also likely, but will be influenced by droughts and associated large-scale fire events. Therefore the southern forest boundary shift northwards could be very uneven, with blocks of forest succumbing to fire or drought in a given year, while in most years there is no apparent range change. Hogg (1994) and Vandall *et al*. (2006) both projected a northward shift in the forest/grassland boundary in the Prairie Provinces with climate change.

Vandall *et al.* (2006) modelled the shifts in Saskatchewan vegetation zones resulting from three climate change scenarios for the 2050s (CGCM2 A21, CSIROMk2b B11 and HadCM3 B21). Vegetation zones in the Great Plains of the United States were used as analogues for the warmer future climates projected for Canada. Results for one of these scenarios are shown in Figure 1 (all scenarios gave similar results). Most of the boreal forest up to 54° latitude is replaced by aspen parkland. Most of the aspen parkland is replaced by mixed prairie. Most of the Canadian mixed prairie is replaced by U.S. mixed prairie (*i.e.* the kind of mixed prairie found in Montana, Wyoming and the Dakotas). The driest area, in southwestern Saskatchewan, shifts to shortgrass prairie, currently found from Colorado southward.

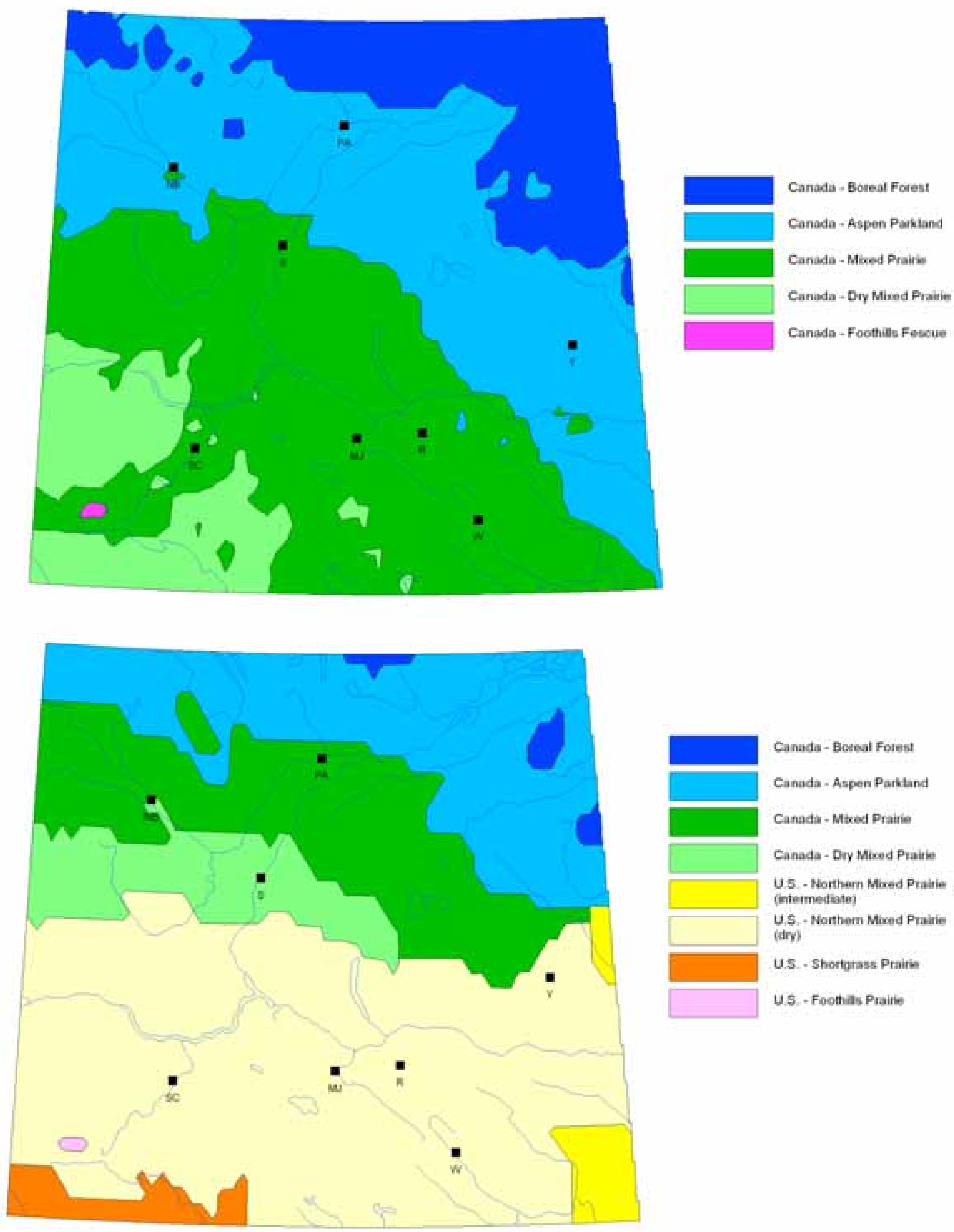


Figure 35. Vegetation zonation in southern Saskatchewan as predicted by ecoclimatic models (Vandall *et al*. 2006). The upper map shows the zonation resulting from 1961-90 climatic normals. The lower map shows the predicted zonation resulting from the HadCM3 B21 scenario for the 2050s.

Henderson *et al*. (2002) examined the special case of climate change impacts on the isolated island forest ecosystems of Moose Mountain and Cypress Hills in southern Saskatchewan (together with similar island forests in neighbouring jurisdictions). As ecotone systems, borderline between grassland and forest ecosystems, the island forests are sensitive to small changes in environmental conditions. As they are relatively small ecosystems, island forests may exhibit lower genetic diversity and greater vulnerability to catastrophic disturbance, such as wildfire, pathogen attack or severe drought.

Henderson *et al*. (2002) employed a range of climate scenarios derived from three GCMs (HadCM3, CGCM2, and CSIROMk2b) to determine the future moisture regimes for the island forests and to consider the implications of these moisture regimes for the dominant tree species. The net effect on moisture levels of the modelled changes in both temperature and precipitation is shown in Figure 2. Increased temperatures will have a powerful evaporation effect, such that soil moisture balances will decline substantially.

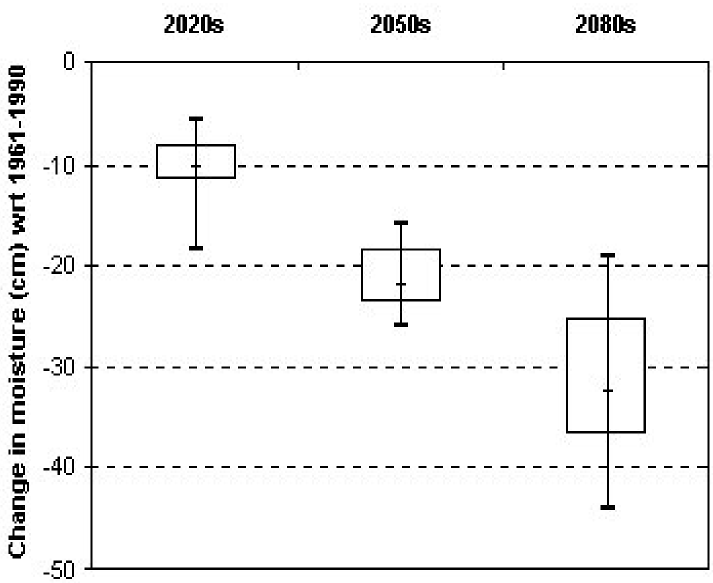


Figure 36: Summary of the projected changes in soil moisture levels (averaged over the five island forest study sites) for the 2020s, 2050s and 2080s. The thin vertical lines in the plot indicate the range of possible future moisture levels compared with the climate of 1961-1990. The boxes indicate the moisture level ranges within which 50% of the scenario projections fall. The horizontal dash within each box indicates the median moisture scenario.

Henderson *et al*. (2002) concluded that the island forests will suffer serious challenges to ecosystem integrity. Highly intensive management will likely be necessary to preserve some type of forest cover at these sites. Possible adaptation actions to maintain forest cover include creating a diversity of age stands, responding aggressively to pathogen disturbances, and regenerating the forest with existing or alien tree species that are better adapted to the new climate parameters.

The Henderson *et al*. (2002) study was a significant factor in the adoption by Saskatchewan's Cypress Hills Provincial Park of a vegetation regeneration plan which aims to create a diverse age stand mix in the lodgepole forest.

Saskatchewan also has important northern island forests in the parkland fringe region just south of the southern boundary of the boreal forest, *i.e.* at the boreal forest / prairie grassland interface. The Nisbet, Fort a la Corne, Torch River and Canwood forests are important examples. Bendzsak (2006) investigated non-native conifer alternatives to the native jack pine and white spruce of the northern island forests, and concluded that red pine, lodgepole pine, ponderosa pine, Scots pine, blue spruce and Siberian larch all show potential for successful establishment, with minimal ecological risk. In a subsequent study Bendzsak (2009) undertook comparative growth sampling of native and non-native conifers, primarily in the southern boreal fringe and in the parkland areas of the Prairie Provinces. This study found that on productive sites red pine, Scots pine and Siberian larch had higher growth volume rates than the native jack pine, while on less productive sites, only Siberian larch outperformed jack pine in a growth volume sense. Lodgepole pine does not seem to outperform jack pine at either site type and, given its susceptibility to mountain pine beetle, might not make the best non-native introduction into the northern forests.

Grassland zones are also projected to change, with aspen parkland and fescue prairie of the present parkland fringe region giving way to variants of mixed prairie. The most significant impacts can be expected to occur at the interfaces of drier grassland with moister foothills grassland, and at the interface of grassland with parkland and forest. In these ecotone areas, the drier ecosystem will expand at the expense of the more humid ecosystem. Modelled shifts in zonation do not specify the exact composition of future vegetation because of differential lags in migration of some species.

In Saskatchewan, grassland production is chiefly limited by moisture supply. While the warmer and drier climate projected for Saskatchewan would suggest declining production and grazing capacity, actual changes in grassland production are likely to be modest given a longer growing season, reduced competition from shrubs and trees, and increases in warm-season grasses that have higher water-use efficiency (Thorpe *et al*. 2004, Thorpe 2007).

Mixed prairie is dominated by cool-season species (*i.e.* plants with the C_3 photosynthetic pathway). However, warm-season species (*i.e.* plants with the C_4 photosynthetic pathway) are relatively more abundant in U.S. mixed prairie than in Canada, and they are dominant in the shortgrass prairie (Vandall *et al*. 2006). Because higher temperatures are required to initiate the growth of warm-season grasses in spring, cool-season grasses have a competitive advantage in cooler climates with shorter growing seasons. Climatic warming will allow warm-season grasses to develop earlier in spring, which may increase their ability to compete with cool-season grasses in northern areas (Long and Hutchin 1991). Climate change modelling has shown increasing proportions of warm-season grasses, and in some cases a shift to warm-season dominance, in the northern part of the Great Plains (Coffin and Lauenroth 1996, Epstein *et al*. 2002). Epstein *et al*. (2002) suggested that the higher water-use efficiency of warm-season species could lead to higher productivity and/or reduced transpiration at a given level of precipitation. However, changes in the seasonality of moisture availability may also affect the proportion of warm-season grasses (Paruelo and Lauenroth 1996, Winslow *et al*. 2003). Most scenarios project a lower proportion of precipitation in summer, and this could moderate the increase in C_4 grasses favoured by rising temperatures.

Some change could occur by shifts in the abundance of species already present. Warm-season grasses such as blue grama (*Bouteloua gracilis*), sand reed grass (*Calamovilfa longifolia*), sand dropseed (*Sporobolus cryptandrus*), and little bluestem (*Schizachyrium scoparium*) are already widespread in the Prairie Provinces grassland biome, and they could expand relative to the cool-season dominants such as wheat grasses (*Agropyron* spp.) and spear grasses (*Stipa* spp.). However, some of the change could occur by migration into Canada of species that are currently absent or rare. Wolfe and Thorpe (2005) compared sand dunes in the Canadian Prairies with their warmer-climate analogues in Colorado and Nebraska. While many species are common to both areas, there are also many (mostly C_4 grasses) that are found in the south but not in the north (*e.g.* sand bluestem [*Andropogon hallii*], sandhill muhly [*Muhlenbergia pungens*], and switchgrass [*Panicum virgatum*]). Future vegetation on dunes could be a mixture of species we already have with migrants from the south. The shift in zonal vegetation from mixed prairie to shortgrass prairie shown in Figure 1 could occur initially by an increase in blue grama – the northward migration of buffalo grass (*Buchloe dactyloides*), the other major component of U.S. shortgrass prairie, will likely be a much slower process. The likely source of migration would be adjacent patches of native grassland further south. For this reason, the current fragmentation of grassland by cultivated fields, roads, etc. will be an impediment to migration of new species.

Sykes (2008) used a simulation model to predict changes in botanical composition of grasslands at Saskatoon and Melfort. Under the current climate (1961-90), plains rough fescue (*Festuca hallii*) was predicted to be the dominant species, while climate change scenarios for the 2020s, 2050s, and 2080s caused a gradual shift to dominance by northern wheatgrass (*Elymus lanceolatus*). This is consistent with the shift from aspen parkland to mixed prairie shown in Figure 1.

Climate change impacts will be significant in Prince Albert National Park (Scott and Suffling 2000). The park can expect increases in forest fire frequency and intensity, increased forest disease outbreaks and insect infestations, and loss of boreal forest to grassland and temperate forest (De Groot *et al*. 2002). Climate change represents “an unprecedented challenge for Parks Canada” and “current ecological communities will begin to disassemble and ‘resort’ into new assemblages” (Scott and Suffling 2000).

Estimating the timing of changes in vegetation zoning or other major ecological shifts is difficult, in part because of the difficulty in predicting precise thresholds. Vegetation responds after the fact to climate change (autonomous adaptation), and it is natural for a given ecosystem to be “behind” environmental conditions to some degree, a condition termed ecological inertia. Anderson *et al.* (1998) warned that ecosystems can absorb stresses over long periods of time before crossing a critical threshold, which may lead to rapid ecosystem and landscape modification. The climate change impact on mature trees, for example, is not likely to be noticeable until biological thresholds are reached and dieback results (Saporta *et al*. 1998). Climate driven change can sometimes be fairly obvious, for example, when driven by a prolonged drought. But it can also be subtle and almost imperceptible, even though major changes are occurring. An example is the slow decline of western North American old growth forests, where old trees are dying at increasing rates without replacement, likely as a result of increased aridity and warmer temperatures (van Mantgem 2009).

Changes in the timing of biological events

Early settlers and Aboriginal people recognised the timing of biological events as a function of season and weather, and used these indicators to forecast the timing and success of planting, fishing and hunting activities (Lantz and Turner 2004). The dates and rates of spring flowering of widely distributed wild plants are among the most reliable events that can be monitored and used as an index of weather and climate. A program called "Plantwatch" monitors the phenology of flowering of key wild plants through the reports of a network of volunteers and has become an important tool for tracking the impacts of changing climate (Beaubien 1997). Dates of flowering of key perennial plants in Alberta are closely related to the average temperature two months prior to bloom (Beaubien and Freeland 2000). A 26-day shift to earlier onset of spring has already occurred over the last century (Beaubien and Freeland 2000). It can be assumed that the life-cycle timing of many other organisms, for example, insects dependent on plant host life-cycles, is also being strongly affected. A 26-day shift in the timing of spring represents a major change and, although the data pertains to Alberta, is very likely also representative of the trend in Saskatchewan over the same time period.

Wildlife

The prairie pothole region of central North America is the single most productive habitat for waterfowl in the world, with the Canadian Prairies producing 50% to 80% of the Canadian duck population (Clair *et al*. 1998). As a long run trend, increasing aridity in the prairie grasslands is likely to negatively impact migratory waterfowl populations (Poiani and Johnson 1993, Johnson *et al*. 2005) as waterfowl numbers decrease in response to drought and habitat loss (Bethke and Nudds 1995). Larson (1995) predicted that a 3°C rise in temperature with no change in precipitation would result in 22% and 56% declines in the number of wetland basins in the grassland and parkland regions, respectively. This trend may be masked by year-to-year fluctuations in moisture levels. In fact, weather fluctuations during the breeding season account for more than 80% of the variation in the population growth rate of mallards and other ducks (Hoekman *et al*. 2002). In northern regions, earlier dates of disappearance of snow and increasing average temperatures have resulted in earlier nesting and hatching of geese (LaRoe and Rusch 1995).

Wildlife migration patterns and population size have already been affected by recent climate trends, and further impacts are expected (Inkley *et al*. 2004). This will affect hunting-based industries, fishing activities and management, and traditional ways of life reliant on vertebrate biodiversity. At the 2004 Prince Albert Grand Council Elders' Forum, elders reported changes in species distributions, changes in plant life, and decreasing quality of animal pelts (Ermine *et al*. 2005).

On a global scale, Wilcove (2008) concluded that migratory species of all kinds are at risk from climate change and other disturbances, as they are vulnerable to disruption at the end points of their journeys as well as along the way. The majority of Saskatchewan bird species are migratory, and there have been notable declines in the numbers of many migratory bird species in North America.

Reptiles and amphibians, often sessile, are also at risk worldwide, though there is little climate-change-related data for herptiles available for the Prairie Provinces. Nor have impacts on insects and still smaller biota been well studied for the Prairies. It can be assumed there will be major impacts, but research in this area would be welcome.

Aquatic ecosystems will be stressed by warmer and drier conditions and a large number of prairie aquatic species are at risk of extirpation (James *et al*. 2001). Many fish species, for example, are sensitive to small changes in temperature, turbidity, salinity or oxygen regimes. For the Prairies, larger algal blooms, accelerated eutrophication, and serious impacts on fish species are expected, owing to a combination of climate change, increasing nutrient runoff, and increasing human use pressures on natural water systems (Schindler and Donahue 2006). Salinities of lakes across the Prairies are expected to increase due to elevated aridity over the next decades (IPCC 2008). Because many lakes in southern Saskatchewan already have salinity-limited fisheries, rising salinity is a recreational and economic concern, as well as an ecological concern. Melville (2001) expects climate change to stress lake environments throughout the boreal plains area of the Prairie Provinces, and advocates reducing allowable fish catches as an adaptive measure. Baulch *et al.* (2005) simulated climate change by warming the littoral zone of a boreal lake and examining the impacts on benthic communities, particularly on the epilithon (the biofilm, consisting of algae, bacteria, fungi and invertebrates, present on submerged rocky surfaces). They predicted increased metabolic rates of epilithons, but note many uncertainties about benthic impacts. Climate change impacts on aquatic ecosystem health is a relatively under-researched field in Saskatchewan - more research in this area would be of great value.

In summary, range distribution changes of almost every animal seem likely. For example, Pitt *et al.* (2008) concluded that winter severity is the principal constraint on the northern range limit of raccoons; therefore this animal can be expected to expand northward under milder winter conditions. McCarty (2001) documented rapid northward range expansions of some animal species and local extinctions at southern edges of ranges owing to recent climate change. All fauna can be expected to show impacts in some manner as vegetation change accelerates.

Adaptation

Conservation policy can aim to extend ecological inertia, have no impact on it, or reduce it (Henderson *et al*. 2002). Vegetation associations that are most “in tune” with the evolving climate will require the least degree of human intervention. Conversely, those vegetation ensembles outside of their natural climate norms will require increasingly intensive and active human intervention and management to survive. However, with a high degree of human intervention it will be possible in some sites to maintain vegetation (and associated fauna) that would otherwise certainly disappear. But it will take financial and human resources, and public will to do so.

Henderson *et al*. (2002) formalised the options for responding to climate change impacts in the Prairie Provinces. They presented three possible natural systems management models. The first is a laissez-faire model, where the assumption is that protected landscapes are best left untouched by human management, so far as possible. In vulnerable forest systems this approach would open the way to sweeping, sudden change, perhaps by major fire or insect disturbance, followed by an ecosystem shift that cannot be defined in detail, but which would almost certainly result in a landscape with greatly reduced tree cover. Over the long run, the passive approach may fail to protect some aspects of biodiversity. The second model assumes that the ecosystem structures and processes present on a particular landscape at some given point in time are the correct or ideal ones. An example is the operative vegetation management plan for Duck Mountain Provincial Park in Saskatchewan, which targets the restoration of the grassland component of that park to its pre-European areal extent (Wright *et al*. 1995). But from a practical standpoint, as climate change advances it becomes increasingly difficult, and eventually materially impossible, to maintain any historic ecological landscape. The third model accepts landscape change driven by climate change as inevitable, but by active management seeks to strategically delay, ameliorate and direct change. Lopoukhine (1990) suggested that active management is the only alternative for protected areas given the reality of climate change impacts. Scott and Suffling (2000) agreed that active management is warranted in response to climate change and noted that intervention strategies will often be species specific. Actively managed change is a conservation model employed in Britain – for example, in response to loss of coastal conservation areas as a result of sea-level rise, new salt-water marshes are created as offsets. At specific sites, actively managed change can be both controversial and expensive.

As an adaptation to address the general parks and protected areas challenge, Henderson *et al*. (2002) stated that “In a world of climate change, selection of protected areas may need to focus on site heterogeneity and habitat diversity (as these provide some buffer against climate change) rather than on representativeness.” For example, high relief terrain, such as the Cypress Hills landscape, can always be expected to provide a range of habitats and ecosystems different from the surrounding plains, and therefore contribute to biodiversity, even as the nature of these habitats and ecosystems changes over time. However, a low relief landscape, such as Prince Albert National Park, which is mandated to protect fescue grassland, aspen parkland and southern boreal forest within the national parks system, may fail to preserve these landscape elements over time.

Zoning, which is already employed as a management technique in many protected areas, will be a critical intra-site management tool. Zoning can facilitate a differentiated response to climate change and a shift towards multiple target landscapes within a protected area, with some zones proactively managed in response to climate change while other zones are managed passively or more traditionally. A multiple-target landscape approach would promote landscape diversity and ecosystem robustness and also have scientific and monitoring value (Henderson *et al.* 2002).

Increasing connectivity between protected areas to facilitate migration of particular species populations is commonly proposed as one method of coping with climate change (*e.g.*, James *et al. 20*01, Malcolm and Markham 2000, Joyce *et al*. 2001). Although some species might be able to migrate, others will be threatened by the arrival of new competitors or by the pathogens that increased connectivity supports. Thus increased connectivity is a two-edged sword and may actually hasten the decline of some ecosystems by favouring alien invasions. Invasive non-native plants and animals are already a major concern for biodiversity and conservation managers – climate change will exacerbate this. However, as new species arrive, and ecosystems evolve, in some cases it will be a question of perspective as to whether a given ecosystem is being lost or whether in fact it is simply adjusting to a new climate regime.

Migration between many of Saskatchewan's waterbodies is not naturally possible for many species, and management choices will need to be made about inter-basin species transferrals. There is a long history of fish-stocking in the Province, and as waters warm and become more saline, some lakes with naturally reproducing fish populations will need to be stocked to maintain species of interest. There may also be a need to stock different fish species at currently stocked lakes. However, in their analysis of climate change impacts on global freshwater fisheries Ficke *et al.* (2007) cautioned that the introduction of fish species is "not a decision to be made lightly because of the possible negative consequences for organisms already in that environment."

The most drought-hardy trees that could potentially survive in an increasingly arid Saskatchewan derive from central Asia (Henderson *et al*. 2002), and Bendzsak (2009) has noted the success of Scots pine and Siberian larch in Prairie Provinces forestry plantations. But while acknowledging that intentional introduction of a non-native species may be a useful tool for adaptation to climate change, Thorpe *et al*. (2006) concluded that trees sourced from within North America are less likely to be ecologically disruptive than Eurasian-origin exotics. Western conifers such as Douglas-fir and ponderosa pine, and hardwoods of the southern prairies such as Manitoba maple, bur oak and green ash, may be suited to future climates of the western boreal forest (Thorpe *et al*. 2006). Red pine (native to the eastern boreal forest) may also be suited to productive sites in the western boreal (Bendzsak 2009).

In restoration ecology, "it is often assumed that understory vegetation will establish over time ('plant trees and the rest will come'), but natural invasion may not automatically bring back all species desired" (Frelich and Puettmann 1999). The impacts of exotic tree introductions into prairie forests on native mid- and understory vegetation are not clear. Furthermore, if one is willing to introduce non-native trees to sustain a forest, logically it may also make sense to consider the appropriateness of the introduction of mid-story and understory forest elements, if they could add to forest resiliency. Such judgments are technically very difficult. Thorpe *et al*. (2006) emphasised the careful steps that need to be undertaken before widespread introduction.

The deliberate widespread introduction of non-native tree species into Saskatchewan forests would also require changes to public policy, as the current presumption is to control and eradicate alien species (Thorpe *et al*. 2006). Stakeholder groups and the public would need to be involved in such decisions. As current awareness levels of the impacts of climate change on ecosystems are low, and as public input is needed to guide land managers in a changing climate future, an effective impacts communications strategy is required (Henderson *et al*. 2002). In fact, a sustained communications strategy – perhaps focussed on protected areas and on key provincial and federal parks – is an essential required adaptation strategy.

Not only the public, but policy-makers too, need to become better informed. At the best of times, it is a challenge to effectively communicate issues, data, research, and management options and consequences between researchers and decision-makers or implementers. When the issues are complex, as they are for ecosystems, the challenge is especially great.

One important practical adaptation measure will be effective environmental and ecological monitoring. We need to follow trends and developments in the health, numbers and distribution of keystone species such as aspen across the region. We also need to follow the status of many increasingly threatened species, and also of invasives. Both an individual species and a holistic ecosystems monitoring approach is important. We need to pay particular attention to relatively understudied and under-monitored climate impacts on ecosystems. Historically we have had a research focus on harvested species, such as big game, waterfowl, and commercial trees – we also need to pay equal attention to threatened elements, such as amphibians, declining migratory songbirds, terrestrial invertebrates, and vulnerable trophic networks in sensitive aquatic ecosystems.

Conclusions

Saskatchewan faces major climate change impacts on ecosystems and landscapes. These climate change impacts combine and interact with other ongoing human impacts. The speed of impacts and change is accelerating.

Key climate change impacts on Saskatchewan ecosystems include:

- An increased rate and intensity of forest disturbances, such as fire and pathogens
- Possible loss of forest cover in grassland-forest ecotone regions, such as the southern boreal forest and in the island forests of the grasslands
- Increased stress on aquatic ecosystems from warmer and drier conditions - many prairie aquatic species are at risk of extirpation
- Declines in migratory waterfowl populations with the loss of wetlands
- A potential increase in plant productivity with a longer and warmer growing season and increasing atmospheric CO_2 – at many sites this impact may be limited or overwhelmed by moisture limitations or other constraints
- The evolution of new landscape ecosystems; for example, a drier climate in southern Saskatchewan could potentially support shortgrass prairie currently found farther south

We have many adaptation options, and some alternative choices about future ecosystems, but it will not be possible to maintain Saskatchewan's ecosystems as they were or as we know them now. The new climate-driven reality is that biodiversity managers need to think of themselves not as practitioners of preservation, but as "creation ecologists", since antecedent landscapes can no longer be effectively targeted. We have options, but the past is not one of them. Passivity in the face of impacts may shrink our ecosystem options, particularly in Prairie forests. However, active management entails some risk and expense. Whatever options we choose, the future ecosystems that result from climate change in Saskatchewan will be unprecedented.

SOIL LANDSCAPES

Soil is a major element of Saskatchewan's natural capital and historically the basis for the regional agricultural economy. The climate scenarios outlined above, with longer drier summers occurring more often, could cause Saskatchewan's soil landscapes to respond with local instability and erosion, including:

- Erosion and shallow slope failure caused by less frequent but more intense rainfall;
- More widespread wind erosion and sand dune activity under conditions of increased aridity and more frequent severe drought; dust storms have impacts on health, tourism, transportation and agriculture.
- Risk of desertification over a larger area as the extent of semiarid to subhumid climate expands beyond southwestern Saskatchewan; and
- Soil moisture thresholds below which landscapes are more vulnerable to disturbance and potentially desertified.

Unmanaged soil landscapes

Among the most active landscapes on earth are semiarid valleys and dune fields, such those in the driest parts of Saskatchewan (Lemmen *et al*. 1998). Most of Saskatchewan lies on the Interior Plains. This physiographic region is underlain by poorly consolidated sediments that erode and fail where they are exposed to the forces of wind, water and gravity and where farming or aridity limit the vegetation cover. The most active landscapes are the dune fields and river valleys (Lemmen *et al*. 1998). These landscapes are sensitive to hydrologic and climatic variation and extremes (Lemmen and Vance 1999). Prolonged dry and wet spells have a strong influence on the resistance of soil and vegetation to major hydroclimatic events (strong winds, intense rain, rapid snow melt). The link between aridity and erosion is well established from paleoenvironmental records (*e.g.*, Wolfe *et al*. 2001) and from the monitoring of erosional processes and regional sediment yields (Knox 1984). Less protection of the soil surface is generally given or implied as the cause of higher rates of wind and water erosion in semiarid landscapes. Plants also inhibit erosion because stems, roots and organic matter, and the transpiration of soil water contribute to the infiltration of rain and snowmelt water (Thornes 1985). Should slopes and stream channels become exposed to less frequent but more intense rainfall, erosion and shallow slope failure would be enhanced by the excess soil water and because the protective cover would suffer from the prolonged dry spells between rain storms (Ashmore and Church 2001, Sauchyn 1998).

There are extensive areas of mostly stable sand dunes throughout western Saskatchewan. Soil moisture plays a critical role in the stabilization of dunes. In the Great Sand Hills of southwestern Saskatchewan, a rhythm of reactivation in the last 50 years was matched by the pattern of droughts (Wolfe *et al*. 1995). Widespread reactivation of sand dunes about 200 years ago is correlated with tree-ring records of prolonged droughts of the mid to late 18th century (Wolfe *et al*. 2001). Dune stabilization has occurred since 1890.

The dunes fields have become more stable throughout the last century despite the droughts (*e.g.* 1930s, 1980s) that impacted agricultural land in the region. Most of the sand dunes of the southern prairies were more active prior to European settlement (Vance and Wolfe 1996). This trend could change, however. The drought and increased aridity forecast by GCMs will most likely result in more widespread wind erosion and sand dune activity (Wolfe and Nickling 1997). Natural disturbances like climate variation and change cannot be isolated from effects of land use in sand dune landscapes. Current sand dune activity in the dry core of the Grassland Natural Region serves as a spatial analogue of the potential response of currently stable dune fields on the currently moister margins of the Prairie Ecozone and southern Boreal Forest (Wolfe 1997, Wolfe and Nickling 1997). GCM-based assessments of future vegetation and soil moisture (Thorpe *et al*. 2001) suggest that vegetation will shift towards more open grassland with increased potential for sand dune activity. Climate at the driest sites may exceed thresholds for active sand dune crests. More proactive land use management and stringent enforcement of current guidelines and regulations will be required given this increased potential for sand dune mobility under a drier climate.

Agricultural landscapes

The activities of soil fauna and flora that support soil fertility and structure would be reduced under lower summer rainfall, but probably increased under predicted warmer and wetter spring conditions, because soil fauna expand with increasing temperature (Johnson and Wellington 1980). This could result in more rapid turnover of organic matter and greater soil fertility in some soils, depending on management practices and the other effects of climate change on soil (Anderson 1992). The sustainability and productivity of soil for agriculture and forestry also would be affected by increases in variability of rainfall, which could mean an increase in the frequency and intensity of periods with shortages or excesses of rainfall. The resulting droughts and floods would have immediate impacts on crop production and more long-lasting effects of soil degradation on production (Wheaton *et al*. 2005), and require drought management plans (AAFRD and AAFC, n.d.).

With the modification of about 90% of the Prairie Ecozone for agriculture, 10s of millions of hectares were exposed to soil erosion. Saskatchewan has the largest share of Canada's agricultural land. Soil loss from cropland ranges between 4 and 70 t ha^{-1} yr^{-1} (de Jong *et al*. 1983, Mermut, *et al*. 1983) or 2-3 orders of magnitude higher than on rangeland (Coote 1983). Wind and water erosion are episodic; centimetres of topsoil can be removed during a single event, reversing centuries or millennia of soil formation and rendering land unproductive. Since the 1980s, however, there has been a revolution in prairie soil and crop management to protect crop land from further degradation.

The semiarid to subhumid mixed grassland ecoregion of southwestern Saskatchewan is at risk of desertification by definition: "Land degradation in arid, semi arid and dry/sub-humid areas, resulting from various factors, including climatic variations and human impact" (UNEP 1994). Desertification is an issue, because 1) trends in some socioeconomic variables put land at increased risk of degradation (Knutilla 2003), and 2) climate scenarios of increased aridity and more severe drought. When the ratio of precipitation to potential evapotranspiration (P/PET - the Aridity Index) was computed for 1961-90 and for the 2050s, using output from the Canadian

GCM2 (emission scenario B2), the area of land at risk of desertification (P/PET < 0.65; Middleton and Thomas 1992) increased by about 50% (Sauchyn, *et al*. 2005). This case study provides only a scenario, however, and not a prediction; there is considerable uncertainty in the projection of future growing season precipitation and especially evapotranspiration (see Water Resources). Sauchyn, *et al*. (2005) used an algorithm to compute PET based only on temperature data. Other factors that control ET, specifically wind and humidity, will change with global warming, and the actual ET depends on how much water is left in the soil.

The most plausible climate future for Saskatchewan (see Climate Scenarios) includes a declining net surface and soil water balance in summer, as water loss by evapotranspiration potentially exceeds precipitation to a greater degree. Increased aridity most likely will be realized by more frequent and/or sustained drought. Sustained drought has cumulative impacts and prevents the recovery provided by intervening years of normal to above-average precipitation. Sustained drought has been implicated as the forcing of landscape change on the northern plains (Wolfe, *et al*. 2001). Prolonged droughts, like those that characterized the pre-settlement history of this region, and are forecasted to occur with global warming, are more likely to exceed soil moisture thresholds beyond which landscapes are more vulnerable to disturbance and potentially desertified.

This scenario of future climate and soil moisture conditions demands serious thought about the adaptation required to adjust soil and water management to limit the risk of desertification. Despite the vast area and relatively sparse population of prairie rural Saskatchewan, most of the landscape is managed. Because management practices have more immediate influences on rates of surface processes than climate change (Jones 1993), they have the potential to significantly mitigate or exacerbate the influence of climate. An increase in growing degree days could support a northward expansion of agriculture in Saskatchewan, but this would necessitate an assessment of the sensitivity of these soil landscapes to both climate change and a changed surface cover. Conversely, as the semiarid southwest becomes more arid, the soil landscapes may be at greater risk of desertification.

Adaptation to minimize climate impacts on soil landscapes

Adaptation to minimize the impacts of climate on soil includes protecting soil landscapes from degradation during extreme hydroclimatic events, that is, storms and drought. Soil conservation has been an integral part of the adaptation of farming practices to the dry and variable climate of the interior plains (Sauchyn 2006). A network of experimental farms was established during the 1890s to early 1900s to develop dryland framing practices that prevent wind erosion and mitigate the impacts of drought. The first Canadian government programs to combat land degradation, including the Prairie Farm Rehabilitation Administration (PFRA), were established in response to the disastrous experience of the 1930s, when the drought impacts were exacerbated by an almost uniform settlement of farmland without accounting for variation in the sensitivity of soil landscapes and the capacity of the climate and soil to produce crops.

In recent decades, prairie farmers have achieved progressively higher and more consistent cereal crop yields, while protecting more land from degradation (Sauchyn *et al*. 2005). Land degradation is preventable throughout the subhumid Prairie Ecozone under current climatic conditions, policy framework, and crop and soil management regimes. With better soil, water and crop management, the production of cereal crops has become less vulnerable to climate variability, although not to sustained drought, a case of trading up – accepting vulnerability to large climatic stresses in exchange for exchange for resistance to smaller ones (Fagan 2004). Within the last 20 years, different cropping systems and the adoption of soil conservation practices, specifically reduced tillage and zero-till, have begun to reverse the decline in soil productivity across up to one third of the annually cropped land of the prairies. Acton and Gregorich (1995) estimated that the implementation of soil conservation practices resulted in a decrease in the risk of wind erosion by 7% and water erosion by 11% between 1981 and 1991. More recent statistics (McRae *et al*. 2000) indicate a 32% reduction in the risk of wind erosion in the Prairie Provinces between 1981 and 1996.

Managing soils and land cover to sequester atmospheric carbon dioxide also increases soil fertility and moisture-holding capacity and thus results in higher crop yields. Grazing management also can boost soil organic matter (Schuman *et al*. 2002). Climate change is expected to slightly reduce grassland soil organic carbon, according to ecosystem models based on grassland biogeochemical dynamics (Parton *et al*. 1995). Most prairie agricultural soils already have lost much of their pre-settlement stored carbon (about 50 to 70%, Lal 2003).

Soil conservation is a prime example of a 'no regrets' strategy, since preventing soil loss is beneficial, whether or not the impacts of global warming occur as forecast. Soil conservation practices can be defeated, however, by climate variability: "Severe and widespread erosion could still occur during extreme climatic events and especially during a period of years with back-to-back droughts" (PFRA 2001). Ability to adapt also is subject to capacity and the distribution of cost (IPCC 2001). In most jurisdictions, the cost of a transition to best management practices is borne primarily by the land manager. "Very severe wind and water erosion is dominated by infrequent occurrences of when highly erosive events impact exposed soil. Such events may only happen once during the farming lifetime of an individual farmer, making it difficult to justify the expense and inconvenience of many soil conservation practices." (PFRA 2000: 33).

In the 1980s-90s, soil degradation was a major policy and management issue. The Senate Standing Senate Committee on Agriculture, Fisheries and Forestry held hearings and produced the landmark document "Soils at Risk". Institutional adaptive responses to the soil degradation crisis included the soils component of the Agricultural Green Plan of 1990, and the National Soil Conservation Program (NSCP) of 1989. In the Prairie Provinces, a major component of the NSCP was the Permanent Cover Program (PCP; Vaisy *et al*. 1996). The initial PCP was fully subscribed within a few months, removing 168,000 ha of marginal land (CLI classes 4-6) from annual crop production. PCP II, a 1991 extension to the original program, converted another 354,000 ha. The PCP represents a policy adaptation that has reduced sensitivity to climate over a large area even though this was not an objective of the program nor has this benefit been acknowledged. Mitigation of climate change is a stated objective of the follow up to PCP, the Greencover Canada Program. The Environmental Farm Planning program is another institutional mechanism for promoting and implementing adaptive soil and crop management practices that reduce vulnerability to climate change.

AGRICULTURE

Highlights

Agriculture is a critical sector for reasons of food security and support to communities and the economy. Agriculture also is threatened by climate change, especially in areas such as Saskatchewan where the climate is changing more rapidly than most other agricultural regions. Impacts and responses are already occurring and these are likely to accelerate in the future. Research findings specifically for Saskatchewan are scarce, but literature from other similar regions and a convergence of considerable evidence supports the following main findings:

- Past changes in many agro-climatic variables, including growing season length, accumulated heat units, and precipitation are fairly well documented and often apparent.

- Knowledge of the direction of future changes in important agro-climatic variables is now more certain and is generally consistent with recent changes. Agro-climatic change is a main driver of production changes in agriculture.

- Future climate change impacts on crop production are still uncertain, but are tending to converge upon estimates of average increasing trends in the near-term until certain thresholds of climate change are reached. This trend is then followed by average decreases and interrupted by large losses accompanying severe climatic events, such as droughts and excessive moisture.

- Growth in agricultural productivity would require the best adaptation measures to deal with climate change and other compounding effects. Adaptation needs to be pro-active, effective, innovative, strategic and in some cases, places, and times, significant, including changes to management and policy regimes. Enhanced adaptation would be beneficial now.

- The complex interactions of effects of insects, diseases, and weeds on agricultural production are still not understood well enough to offer substantial findings for projected impacts. The loss of cold winters is contributing to the increasing the risk of some pests, reduced water storage, and other problems.

- Increasing water scarcity is one of the most serious risks for agriculture and society. Projections of temperature increases are more confident than the slight annual precipitation increases, and the resulting higher evaporative demand is a strong driver of water scarcity.

- Although warming winters are generally favorable for livestock production and management, increasing threats of stresses related to heat, water, insects and diseases, and other climate hazards tend to offset gains.

- Extreme weather and climate are "wild cards" whose trends are generally fairly certain, and whose effects are generally detrimental and usually not considered well or at all in future estimates of agricultural production.
- Policies and institutions are currently constrained in their adaptive capacities to deal with climate change by several factors including their weak networks with science and ability to use climate information.
- The past is no longer suitable alone for planning for the future. Climate change information must be mainstreamed into strategic, operational, and policy considerations.

Introduction and Background

> *"The Province (Saskatchewan) is endowed with one of the world's most important agriculture resource bases. The Canadian prairies are ideally suited to dryland crop production, being characterized by a cool climatic regime that naturally controls many diseases and pests…"* (Kerr 2005)

Agriculture is a vital sector for food security and both rural and urban development. Agriculture in Saskatchewan is exposed to among the most extreme climate conditions in Canada. Most of the largest year-to-year differences in production of both crops and livestock are related to weather and climate. Many of the important on-farm and other agri-business decisions are made considering the threats and opportunities of weather and climate. This combination of great exposure, sensitivity, and variable adaptive capacity make agriculture relatively vulnerable. Current and future climate change is adding further stresses and opportunities for agriculture. This means that much better, more proactive, planned and effective adaptation and an enhanced understanding of potential impacts are required.

An improved understanding of climate change impacts on agriculture and the vulnerability of agriculture in the prairie region is crucial because Canada's prominence as a food supplier for the world is expected to increase with climate change (IIASA 2001). Saskatchewan has a main part in this role. This status will come under increasing challenges as its climate suitability for agriculture, such as the "cool" advantage mentioned in the quote at the beginning of this section, comes under increasing pressure from climate change.

Agriculture is important to the Saskatchewan and Canadian economies. In 2003, the provincial GDP was $36,519 billion, of which 8.7% was derived from agriculture (and related service industries),12.3% from other primary industries, and 67% from an increasing range of service industries (Lewry 2005). Because of the large farm land base and small population (and low value-added) the Saskatchewan agricultural economy is largely export-oriented. In an average year, Saskatchewan exports about $2 billion in wheat and $400 million in canola and pulses. In 2002, live animal exports were nearly $400 million and meat exports $130 million (Storey 2005). In 2007, the value of Saskatchewan's total agricultural crop exports was over $5.5 billion and the total value of livestock exports was over $358 million (Saskatchewan Ministry of Agriculture 2009).

This report first describes objectives, scope and method of the work, then discusses current agro-climatic changes, impacts and adaptations. A section on future agro-climatic changes follows, including possible impacts and adaptations. Concluding sections are policy implications, conclusions and recommendations.

Current Agro-Climatic Changes and Impacts

A conceptual framework for understanding climate change and impacts on agriculture is presented in Figure 37. Changing climate, both now and in the future, determines agro-climatic conditions for agricultural activities and production. These conditions, in turn, have consequences for soils, water, plants and animals. Adaptation usually diminishes negative effects. Residual negative impacts are termed adaptation deficits and these should be targeted by pro-active and planned adaptation. The bio-physical impacts have socio-economic consequences that are partly determined by the capacity to adapt and also influence the bio-physical impacts. For example, increased economic returns may encourage increased production for certain crop types. To complete the cycle depicted, increased production and population growth with the associated energy uses may result in increased greenhouse gases and land-use changes which affect the nature and rate of climate change.

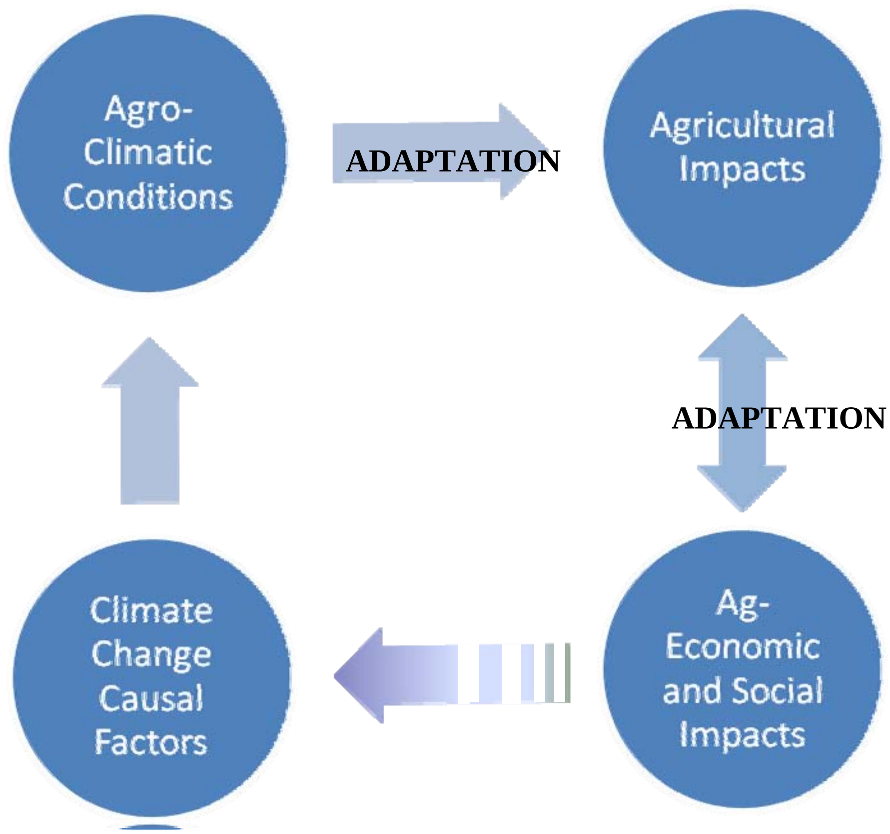


Figure 37. A research framework demonstrating the linkages among climate change causal factors, agro-climatic changes, impacts on agriculture and agricultural adaptation (adapted from Watson 2001 IPCC).

The climate parameters relevant to agriculture in Saskatchewan are changing in our region at rates that may be among the greatest in the world. *et al*The U.S. Climate Change Science Program and the Sub-committee on Global Change Research have recently released an assessment of the effects of climate change on US agriculture, land resources, water resources and biodiversity (Backlund *et al*. 2008). That series of reports have useful findings for agriculture relevant to the Great Plains area, including Saskatchewan.

"Observations also show that climate change is currently impacting the nation's ecosystems and services in significant ways, and those alternations are very likely to accelerate in the future, in some cases, dramatically." (Backlund *et al*. 2008: vii). Climate change, especially over the past 50 years, is showing a persistent pattern with features consistent with the scientific understanding. Greenhouse gas induced warming is now quite significant and has emerged from the large natural variations (Backlund *et al*. 2008: 20).

Greater thermal resources

Mean annual temperatures have already increased during the period of instrumental record. The 12 stations in the Canadian Prairies with the most data since 1895 had an average increase in temperature of 1.6°C, with the greatest warming in spring (Zhang *et al*. 2000). Recent changes to Canadian Prairie climates have already had discernible impacts on agricultural production (*e.g.*, Cutforth 1999, Sauchyn and Kulshreshtha 2008). Increased growing season length has enabled a greater variety of crops and utilizing pasture for longer periods, for example.
Growing season length and warmth controls crop establishment, growth, and maturity. The impacts of changes in growing season length and other climate changes have been documented for both animal and plant biology. Spring phenology shifts in breeding and blooming, for example, have occurred at a rate of about five days earlier per decade during the past 50 years (Root *et al*. 2003).

Ups and downs of water supplies

Water availability is generally the most important climatic factor determining crop yield, especially in southern and central Saskatchewan. Suitable water supplies are also a pre-requisite for livestock production. Water deficits are detrimental to crop yield especially at certain stages of development, therefore timing of plant available water is important as well as amount. Most major crop disasters are caused by extremes in soil moisture and temperature (*e.g.* Wheaton *et al*. 2008, Hengeveld *et al*. 2005). Further details regarding droughts, floods, and their effects are in later sections.

Advantages and disadvantages

Current climatic challenges faced by agricultural producers are numerous and require difficult adaptation, especially when compounded by other non-climatic changes, such as in markets. Although accumulated climate conditions, such as growing degree-days, are important for achieving stages of crops and insects, extremes often cause the most havoc. These challenges include low and highly variable precipitation resulting in droughts and floods (or excessive soil moisture), relatively short growing season length, high temperatures, and storms of various types, including strong winds, hail, lightning, and dust storms. Hot days can have negative effects, especially during sensitive stages such as flowering and have negative effects on yield for crops, fruit trees and shrubs. Hot days can also cause heat stress for people and animals. More about the extremes of water availability are included in other sections of this report.

Alternatively, the climate of Saskatchewan has several advantages for agriculture, especially when used appropriately. For example, most of the precipitation falls during May, June, July when it is most needed. Winter cold is hard on pests and diseases. Snow usually accumulates over the winter season and is the main source of recharge in spring for water supplies such as soil moisture, wetlands, dugouts, and groundwater. Long stretches of less than adequate precipitation, however, especially when coupled with higher than average temperatures, create drought conditions and can result in water scarcity. In summary, the current climate change has many positive and negative effects and complex interactions.

Past and Present Adaptation

Cropping types, farms, farming patterns, and policies have shown considerable change and adaptation in the past decades. Carlyle (2005) shows that farms classified as wheat farms have declined sharply and a corresponding percentage increase in grain, oilseed, and beef cattle farms has occurred. Before 1966, most of Saskatchewan's farms were classified as wheat farms. The 2001 Statistics Canada data showed that of the total number of farms (all types) in Saskatchewan (48,990) 18.4% were wheat farms , 44.3% were grain and oilseed farms , 24.7% were beef cattle farms and other types were 12.6%.

The economics of farming continue to challenge farmers, however, and the trend of relatively high farm cash receipts in the 1980s was replaced by the high cost of farm inputs increasing through the 1990s. In 2003, the realized net income was at a record low negative $390 million. In terms of purchasing power, Saskatchewan farmers were worse off in the 1990s and in the early 2000s than at any time since European settlement, except the 1930s. Farmers have adapted to this situation by expanding and diversifying their operations and increasing efficiency. Another adaptation has been to increase off-farm income - close to 75% of farm household income is now from this source. Organic farming helps to decrease input costs and increase commodity prices. Saskatchewan is the leading province in organic production, which consists mostly of cereals and oilseeds (Storey 2005).

Institutions are important vehicles to adapt to both current and future climate change (Diaz *et al*. 2003). Marchildon *et al*. (2008) explored institutional adaptation to exposure to drought during 1914-1939 in Saskatchewan and Alberta. These droughts provoked major institutional adaptation, including the establishment of the Special Areas Board by the Government of Alberta and the creation of the Prairie Farm Rehabilitation Administration (PFRA) by the Government of Canada. They conclude that the severe and large area droughts, such as in 1988 and 2001-2002, would likely have been much worse without the institutional adaptations and lessons learned from earlier droughts. This emphasizes the advantages of the experience of both producers and institutions with coping with droughts. Such lessons became major adaptation measures, including changes in land tenure, improved land and water conservation practices, plus minimum tillage. Another lesson is that effective political leadership, that is democratically responsive to a population under stress, can have the innovative capacity to create the institutions and the infrastructure needed to facilitate adaptation. The authors also remind us that more will be required of such institutions and of scientific expertise because of the exacerbating influence of climate change.

The knowledge of current adaptation is a good indicator of near-future adaptive capacity. Two of the first studies to extensively document and categorize current adaptations and dynamics of adaptation, using the massive drought of 2001 to 2002 as the example, was Wheaton *et al* (2007) and Wittrock and Wheaton (2007). They found that current adaptation dynamics and strategies have distinctive types, time and spatial patterns. In the Prairie Provinces, the most frequently mentioned types of adaptation were those for crops and livestock, followed by water and economics, then community support and technologies. The study method used was primarily a review of news media, so findings are dependent upon the accurate reflection of society by the media. These types of options and their emphasis indicate the priority adaptations for the 2001-

2002 drought. That drought was very costly and disruptive, even with the active application of much adaptation, suggests that adaptation can be improved, that is, an adaptation deficit exists which must be addressed to deal with future droughts, especially of this size and severity or greater (Wittrock and Wheaton 2007).

Adaptation is most effective in achieving goals of reducing negative impacts if it is implemented properly, facilitated and has few barriers. Documented barriers to adaptation to drought included lack of funds, research and knowledge of water supplies and water use and resistance to making changes. Provincial and national drought and integrated water management planning were considered useful vehicles for reducing vulnerability to water scarcity (Wheaton *et al*. 2007). Effectiveness of adaptation was described by Wittrock and Wheaton (2007) using criteria such as residual negative impacts, positive impacts, opportunities, barriers, mal-adaptations, efficiencies and innovations. Innovations included drought research (*e.g.*, Canada Drought Research Initiative, Stewart and Pomeroy 2005), increased media and web information related to drought monitoring and adaptation, community support, diversification and livestock management. Many adaptation options were recommended for dealing with the 2001-2002 drought. Wittrock and Wheaton (2007) compared these with actual options as another way of evaluating the effectiveness of adaptation. The differences between potential and actual adaptation indicate the room for improvement of the actual adaptation process. A gap existed, but additional options were also documented that did not appear as recommendations. These innovative options included water sharing arrangements, modified farming equipment and community support. The coping range of the agricultural sector and society was found to be frequently exceeded because of the many devastating and costly impacts that were beyond the ability of current adaptation actions. This means that further adaptation research, planning, capacity building, and implementation require urgent attention and support.

Future Agro-Climatic Scenarios

The recent climate change assessment for the Prairies (and Canada) emphasizes two main points: 1) the largest risk is water scarcity, and 2) the past is no longer a sufficient guide to the future (Sauchyn and Kulshreshtha 2008). The similarity of current and future climate trends increases confidence in the forecasting of expected climate trends and reinforces the need for investigating potential impacts and adaptation levels and capabilities. Current climatic challenges for agriculture are changing rapidly in Saskatchewan and the rest of the Prairies, and more attention needs to be paid to these trends to take advantage of them (Cutforth *et al*. 2007).

Future changes in agro-climates will provide a complex mix of both positive and negative impacts (Table 2). Positive impacts and opportunities for agriculture may result from the continued expansion of the warm season, increasing accumulation of heat and milder, shorter winters, depending on adaptation capacity. Alternatively, negative impacts may occur with changes in extreme weather and climate, such as droughts, heavy precipitation, increased variability, changed timing of precipitation, and heat waves. The net impacts are unclear and are heavily dependent on many assumptions including the effectiveness of adaptation, coping range, nature of future farming and the economy, and the characteristics of climate change.

Table 2. Future possible changes in agro-climates for the agricultural Prairie Provinces including examples of possible advantages and disadvantages (adapted from Sauchyn and Kulshreshtha 2008)

Index	Changes (relative to 1961-1990 unless noted)	Period and spatial pattern	Reference	Possible advantages for agriculture[1]	Possible disadvantages for agriculture[1]
Thermal indices:					
Growing degree-days (Base 5°C)	25 to 40% 42 to 45% 30-50%	2050s; greater changes in the north 2050s for Lethbridge and Yorkton	Thorpe *et al*. (2004) CCIS[2] (2002) Barrow and Yu (2005)	More crop options; more crops per year; improved crop quality; shifts to earlier spring and later fall growth	Accelerated maturation rates and lower yields; increased insect activity; changed herbicide and pesticide efficacy
Heating degree-days	-23%	2050s for Lethbridge and Yorkton	CCIS[2] (2002)	Decreased heating costs	
Cooling degree-days	146 to 218%	2050s for Lethbridge and Yorkton	CCIS[2] (2002)	Unknown	Increased ventilation for barns, more cooling shelters and air conditioning
Hot spells: 20-year return period of maximum temperature	1 to 2°C increase	2050	Kharin and Zwiers (2005)	Possible benefits to warm season crops	Heat stress to plants and animals; increased transpiration rates can reduce yields; increased need for water for cooling and drinking
Cold spells: 20-year return period of minimum temperature	2 to >4°C increase from 2000	2050	Kharin and Zwiers (2005)	Decreased cold stress to animals	Increased pests and diseases; increased winterkill potential
Growing season length	15 to 50 days	2050s Largest increases in north	Gameda *et al.* (2005)	More hay crops possible, longer pasture season, higher yielding and greater diversity of crops – all dependent on water availability	Unknown

[1] Most of the advantages and disadvantages are summarized from Wheaton (2004)
[2] Climate Change Impacts Scenarios (CCIS) project

Index	Changes (relative to 1961- 1990 unless noted)[1]	Period and spatial pattern	Reference	Possible advantages for agriculture[1]	Possible disadvantages for agriculture[1]
Moisture indices:					
Soil Moisture capacity (fraction), annual	>0 to <-0.2; mostly drying	2050s; greatest decreases in south to southeast	Barrow *et al.* (2004)	Unknown	Increased moisture stress to crops; decreased water availability
Palmer Drought Severity Index (PDSI)	Severe droughts twice as frequent Worst droughts frequently exceeded in both spatial extent and severity	Doubled CO_2 for southern Saskatchewan Southern Canada Future Decades	Williams *et al.* (1988) Bonsal and Regier (2006)	Advantages for warm season crops and those needing little water	Increased damages and losses from droughts; increased costs of adaptation; increased demand for water for most uses including irrigation
Standardized Precipitation Index (SPI)	Little change	Southern Canada Future Decades	Bonsal and Regier (2006)	Little change if demand for water stays same	Little change
Moisture deficit: annual precipitation minus potential evapo-transpiration (P-PET)	-60 to -140mm (*i.e.* increased deficit of 0 to -75 mm)	2050s 2050s	Gameda *et al.* (2005) Nyirfa and Harron (2001)	As for droughts As above	As for droughts As above
Aridity Index (AI): ratio of annual precipitation and potential evapotranspirat-ion (P/PET)	Area of AI <0.65 increases by 50%	2050s	Sauchyn *et al.* (2005)	As above	As above
Number of dry days: time between 2 consecutive rain days (>1mm)	Modest to insignificant changes	2080 to 2100	Kharin and Zwiers (2000)	As above	As above
Number of rain days	Modest and insignificant changes	2080 to 2100	Kharin and Zwiers (2000)	Little change	Little change
Precipitation extremes: 20-	Increase of 5 to 10 mm and	2050	Kharin and	Potential water for storage	More flooding and erosion concerns; more

year return period of annual extremes	return period decreases by about a factor of 2		Zwiers (2005)		difficult planning for extremes

Index	Changes (relative to 1961- 1990 unless noted)[1]	Period and spatial pattern	Reference	Possible advantages for agriculture[1]	Possible disadvantages for agriculture[1]
Other indices:					
Wind speed, annual	<5 to >10%	2050s	Barrow *et al*. (2004)	Greater dispersion of air pollution	Greater soil erosion of exposed soils; damage to plants and animals
Wind erosion of soil	16% -15%	Doubled CO_2 Doubled CO_2	Williams and Wheaton (1998)	None	Damage to soil, increased soil deposition problems, health and many other concerns
Incident solar radiation	<-2 to <-6 W/m^2	2050s; greatest decreases in north central	Barrow *et al*. (2004)	Decreased radiation may partially offset heat stress	Reduced plant growth if thresholds are exceeded Possibly less energy from solar sources
Climate Severity Index[3]	-3 to -9	2050s greatest improvements in AB, and MB; fewer in SK	Barrow *et al*. (2004)		Less severe climates for outside work; more suitable for animals
Carbon Dioxide	Various emission scenarios used (*e.g.*, 1% per year)		Leggett *et al*. (1992) Easterling *et al*. (2007)	Increased plant productivity especially with C3 plants, depending on other limits	Possible reduced quality of yield

The main limitation, advantages and disadvantages, as summarized by Sauchyn and Kulshreshtha (2008) include decreased water availability (*e.g.* soil, surface and groundwater) and increased intense rainfalls; higher temperatures (insect and diseases), decrease in snow cover amounts and season, increases in many extremes, increased accumulated temperatures, and increased growing season length (Table 2). The net impacts are very difficult to determine, especially with the lack of integrated modeling capability. Important concerns for farmers are the effects of weather and climate on growth and yield of crops, management of crops (*e.g.*, seeding, pest control, inputs, harvesting) and livestock management (*e.g.*, feeding, calving, pest control,

[3] Climate Severity Index (CSI) is an annual measure of the impact of climate on human comfort and well-being, and of the risk of certain climatic hazards to human health and life, with a scale ranging from 0 to 100 (Barrow *et al.*, 2004); higher CSI indicates more severe climates; severity is weighted equally between winter and summer discomfort factors, and psychological, hazards and outdoor mobility factors.

shelter). Climatic impacts on agricultural regions of other countries, competitors in the global market, also affect prairie agriculture.

Types of future agro-climatic changes are organized into three main types: thermal, moisture and extreme event changes (Sauchyn and Kulshreshtha 2008). Examples of these types are:

Thermal Changes

- Increased growing season length, heat accumulation (degree-days) and heat stress
- Decreased cold spells, cold accumulation (degree-days), and cold stress
- More frequent and intense heat waves

Moisture Changes

- Increased winter rainfall and snow melt events
- Longer dry spells
- Decreased snowfall totals, snow cover depth and duration of snow season
- Risk of decreased summer precipitation
- Longer and more intense potential evapo-transpiration season resulting in more water loss
- Less water in dugouts, reservoirs, streams, lakes and wetlands related to increased potential evapo-transpiration amounts and seasons and snowpack decreases

Extreme Events

- Increased intensity, duration, frequency and intensity of droughts
- Decreased risk of frosts
- Increased wind speed, peak wind events, and damage
- Increased risk of intense rainfall, excessive moisture and flooding
- Increased risk of soil erosion by wind and water

Other

- Increased demands for water and related conflicts
- Northward shifts of the range of crops, weeds, insects and diseases
- Decreased water and air quality related to higher temperatures

McGinn and Shepherd (2003) used two versions of the Canadian Global Climate Model to drive the modified Versatile Soil Moisture Budget (mVSMB) model to assess changes in soil moisture, aridity, and other agro-climatic indices, and seeding and harvesting dates, growth and water use of spring wheat (*Triticum aestiv*um L.) in the Canadian Prairies. The autonomous adaptive strategies explored were earlier seeding and harvesting dates and they were found to be useful. Changes in yield were not estimated, but shorter periods for maturation were simulated resulting from higher temperatures. Shorter maturation periods are reported to decrease grain yield of spring wheat (*e.g.* Laurila 2001, Hatfield *et al*. 2008). The newer climate scenario projected an increase in growing degree-days, slight decrease in aridity, slight increase in average growing season soil moisture in Saskatchewan. This increase in soil moisture is attributed to the shift to earlier seeding and harvesting adaptations that avoid the more arid conditions in the summer, the shorter maturation period and the increase in precipitation projected by the GCMs used (McGinn and Shepherd 2003).

It is important to note that the potential increase in annual precipitation projected by the GCMs used by McGinn and Shepherd (2003) and others, is estimated with much less confidence than the change in temperatures, and the use of several scenarios with a wider range of conditions is recommended by the Intergovernmental Panel on Climate Change (IPCC). More recent global climate model scenarios are described earlier in this report. The increased annual precipitation does not necessarily translate into more available moisture as it is likely to be offset by increased daily temperatures, resulting in increased potential evapo-transpiration and a longer evaporation season. Also summer dryness is consistently projected and this is the season with highest demand for water. Most other studies that examine more of the entire growing season find that aridity increases and soil moisture decreases (Table 2).

The understanding of the complex climate system and of possible future climates has increased considerably in recent years (*e.g.* Solomon *et al*. 2007). The nature and sources of reliability and uncertainty are becoming clearer. Confidence in precipitation patterns and nearer term projections (*e.g.* 2020s), for example, is increasing. Winter increases and summer decreases of precipitation are projected. Barrow *et al*. (2004) and Barrow and Yu (2005) provide information not only regarding future climates and extremes, but also past climates. The Canadian Climate Scenarios website has also added climate scenario information recently (CCCSN 2009).

Researchers are finding that a direction of change in biomass production and yields is reached at certain thresholds. Climate change scatter-plots for the grassland region of the Prairie Provinces show the simulated changes in mean annual temperature and precipitation for three future periods of the 2020s (2010-2039), 2050s (2040-2069) and 2080s (2070-2099) (Sauchyn and Kulshreshtha 2008, Barrow 2009). Temperature and precipitation are the variables used as they are important aspects of the more complex variables such as soil moisture, droughts, floods, and growing season length. These plots provide much information, including the finding that the forecast climates are beyond the range of natural variability for all the scenarios depicted. This means that the climates projected and their impacts are beyond the current experience, even for the earliest period of the 2020s. Experience is important in dealing with impacts, so this finding implies difficulties and barriers for adaptation and likely increasing vulnerability to such new climates.

It is important to note that all of the several climate change scenarios described in Sauchyn and Kulsthreshtha (2008) and Barrow (2009) project climates that are outside the range of natural variability experienced and observed in the 20th C. This means that the agro-climates and their impacts are expected to be beyond historical experience. Experience plays a large role in the ability to adapt, so this amount of climate change makes adaptation more difficult and therefore makes agriculture more vulnerable. An example of this change is the shift of severe drought farther north in the Canadian prairies as compared with several other historical droughts (Wheaton *et al*. 2008).

The spatial variation of precipitation changes over the prairies (Barrow 2009) shows the largest annual precipitation decreases for the 2020s to be in northwestern and southern agricultural Saskatchewan (*i.e.*, Regina and southward). The largest range of change among several climate scenarios appears to be in southwest Saskatchewan. This means that the driest part of the prairies is expected to become even drier, with increasing variability. Both of these aspects point to increasing challenges for agriculture and increasing need for enhanced adaptation.

A favorable result of continued warming and longer growing seasons is the possibility of increased productivity and diversity of crop and animal production. This benefit would be only available where adequate moisture exists at the proper time and this appears to be a less certain outcome. Consideration of integrated net effects of climate change is a research gap. What factors will combine to cause larger impacts and require enhanced or perhaps different adaptation measures? What interaction among stresses can be expected? Surprise impacts may be more possible with new interactions of vegetation and management, for example. Even though some impacts may potentially be positive, it they occur too quickly, adaptation may be difficult and opportunities could be lost.

Future Climate Change Impacts and Adaptations

Changes in crop growth and production

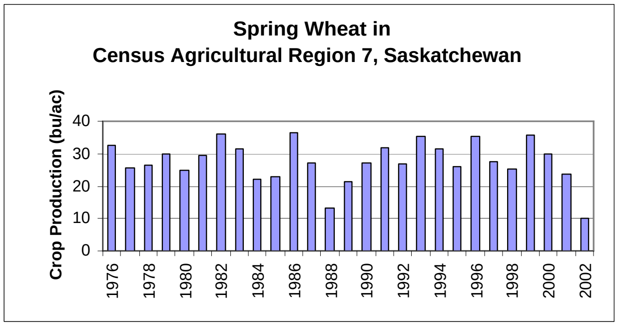
In terms of main crop types and production patterns, spring wheat remains the main crop (in terms of area), but it no longer dominates production. By 2004, spring wheat occupied the largest area of major crops grown in Saskatchewan, but specialty crops and canola are a close second and third, and barley and durum wheat were a close fourth and fifth (Storey 2005:37). By 2008, canola had exceeded spring wheat by harvested area, although the 2003-2007 average wheat area remains the highest for crop type. Dry peas and lentils are the main specialty crop types in terms of harvested area (Saskatchewan Ministry of Agriculture 2009). Because of the past dominance of spring wheat, however, it is a logical choice for impact assessment and has been used for most modeling experiments.

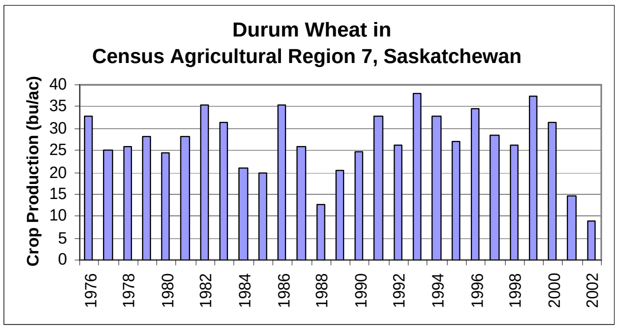
The main limiting factors to crop production in Saskatchewan are dry-land soil moisture and relatively short growing season length. The most critical limitation for crop growth and yield on the prairies is the availability of soil water (*e.g.* McGinn and Shepherd 2003, Sauchyn 2007 in Wall *et al*., Chen *et al*. 2008). The major impacts of climate change on the Prairie Provinces are expected to be the loss of soil moisture and surface water (Diaz and Gauthier 2007 in Wall). Climate change scenarios for the prairies (Barrow 2009) show an increase in temperature and reductions in summer precipitation. Even increases in precipitation may not provide increases in plant available water because of the increased evaporative demands (Li *et al*. 2007). Also soil recharge tends to be greater during the spring and during less intense rainfalls, which are expected to decrease with climate change.

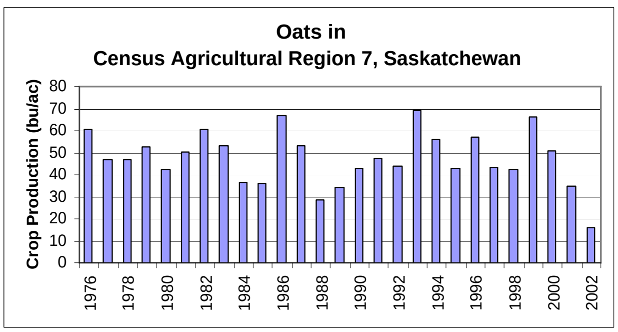
Climate change is expected to result in minimum temperatures increasing more rapidly than maximum temperatures. Limits to plant physiological processes related to high temperatures have been documented. For example, increased minimum temperatures may cause increased respiration, resulting in reduced yield potentials. Temperatures exceeding the optimal for biological processes often result in sharp decreases in net growth and yield (Rosenzweig and Hillel 1998). The maximum rate of photosynthesis in C3 plants occurs at 20 to 30°C (Crafts-Brander and Salvucci 2002). Temperatures also drive evapo-transpiration. Bullocks' (2008) preliminary results show that actual evapo-transpiration is fairly well correlated with spring wheat yield and quality.

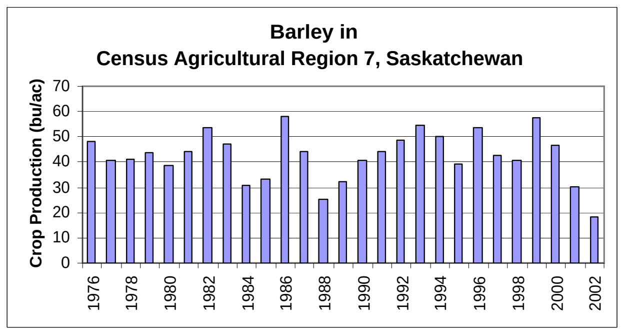
Critical temperature and plant available water are also being used to assess crop growth and yield impacts of climate change. Crop species differ in their critical temperature range for life cycle development. Growth begins at a base temperature and plants develop best at an optimum temperature. As temperatures increase, plants with lower optimum temperature show yield decreases before those with a higher optimum temperature. Poor yield and performance occurs when the optimum temperature is exceeded. Wheat is an important crop in Saskatchewan and can be used as an indicator of the performance of several other crops. Wheat yield in the Great Plains of the U.S. is estimated to decline 7% per 1°C increase in air temperature from 18 to 21°C and about 4% per 1°C increase in air temperature above 21°C. About 34° C is the temperature at which wheat fails to reproduce. This estimate does not include reductions in photosynthesis or grain-set, and these could also occur (Backlund *et al*. 2008).

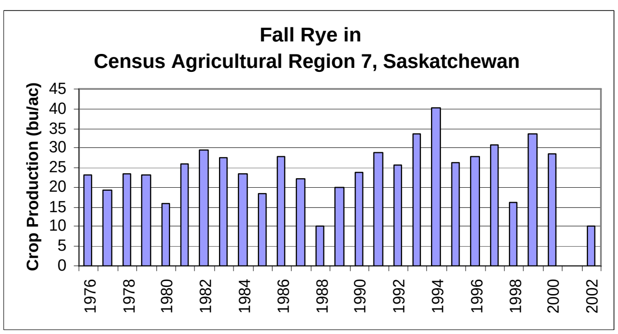
Some of the largest year-to-year changes in yield are related to climate variability (Williams *et al*. 1988, Wittrock 2005, Hatfield *et al*. (2008) both directly and indirectly through effects on insects, diseases, and weeds. Lobell *et al*. (2007) used simple measures of growing season temperatures and rainfall to show that nearly 30% of the year-to-year variation in global average crop yields could be explained by these measures. During the droughts of 2001 to 2002, crop production in the Prairie Provinces was generally below to well below average as compared with historical yields (Wittrock 2005). Provincial production of spring wheat dropped 20 to 35% below the 1991-2000 average,. The previous low-yield year was the severe drought year of 1988. An example time series is shown for selected crops for the central grain belt to demonstrate the sharp decreases in the yields for many crop types during the 2001-2002 drought years (Figure 38). Several crop types, such as spring wheat, durum wheat, barley and oats, exhibited record low yields in the 2002 drought year.

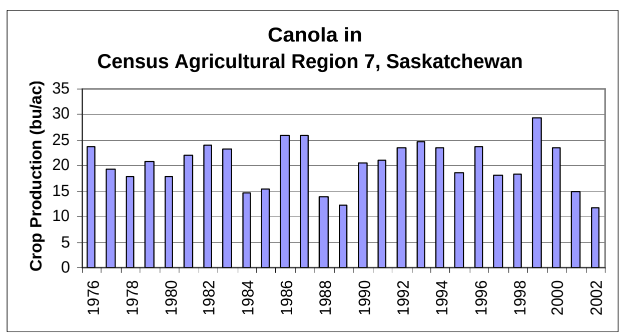

Spring Wheat in
Census Agricultural Region 7, Saskatchewan
Crop Production (bu/ac)
0 10 20 30 40
1976 1978 1980 1982 1984 1986 1988 1990 1992 1994 1996 1998 2000 2002


Durum Wheat in
Census Agricultural Region 7, Saskatchewan
Crop Production (bu/ac)
0 5 10 15 20 25 30 35 40
1976 1978 1980 1982 1984 1986 1988 1990 1992 1994 1996 1998 2000 2002


Oats in
Census Agricultural Region 7, Saskatchewan
Crop Production (bu/ac)
0 10 20 30 40 50 60 70 80
1976 1978 1980 1982 1984 1986 1988 1990 1992 1994 1996 1998 2000 2002


Barley in
Census Agricultural Region 7, Saskatchewan
Crop Production (bu/ac)
0 10 20 30 40 50 60 70
1976 1978 1980 1982 1984 1986 1988 1990 1992 1994 1996 1998 2000 2002


Fall Rye in
Census Agricultural Region 7, Saskatchewan
Crop Production (bu/ac)
0 5 10 15 20 25 30 35 40 45
1976 1978 1980 1982 1984 1986 1988 1990 1992 1994 1996 1998 2000 2002


Canola in
Census Agricultural Region 7, Saskatchewan
Crop Production (bu/ac)
0 5 10 15 20 25 30 35
1976 1978 1980 1982 1984 1986 1988 1990 1992 1994 1996 1998 2000 2002

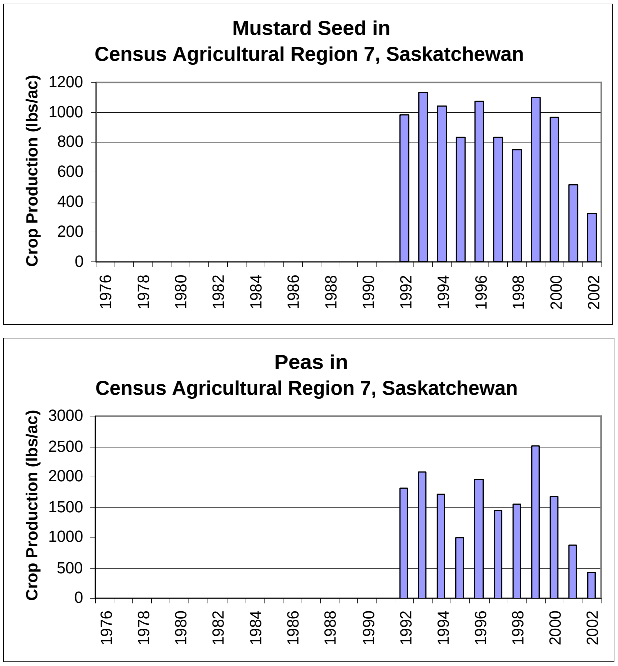


Figure 38. Yields of selected crops for census agricultural region 7, Saskatchewan (Wittrock 2005, Data source: Statistics Canada 2003)

Modeling crop response integrates the many climatic, soil and other factors affecting growth and yield. Williams *et al*. (1988) were among the first to model the effects of climate change on crop yields. They estimated spring wheat yields using relevant historical periods of interest and future climate change scenarios for Saskatchewan. The wheat model is physically based and was developed by the Food and Agriculture Organization (FAO 1978). The model results were tested with observed data for dry matter yield and found to be within 15% of observed values. This comparison is good, considering that many environmental factors affecting crop growth and productivity, such as weeds, insects, diseases, are not accounted for in the model. The sensitivity analysis of the crop yield model was useful to assess the effects of temperature and precipitation on potential yields (Williams *et al*. 1988). They clearly demonstrate that for temperature increases, a corresponding increase in precipitation is required to maintain wheat yields because of the effect of moisture stress. For example, precipitation increases of about 40% would be required to maintain existing yields if temperatures increased by 3°C. Note that the projected increases for the climate change scenarios described earlier are well below 40%. The rate of heat accumulation is a key factor affecting crop development and yield. The higher the temperature, the faster spring wheat matures, and the lower the yield.

Results suggest that Saskatchewan's average spring wheat yields under a long-term change in climate as represented by the Goddard Institute for Space Studies Climate Model (at the time of doubled atmospheric carbon dioxide levels) would be 18% below the average (Williams *et al.* 1988). If the projected precipitation increase did not occur, yields fall 28% below average. In terms of spatial changes, the most striking feature is the greater negative effect in the northern agricultural region as compared with the south and the shift towards greater homogeneity in impacts on spring wheat maturation and production.

Williams and Wheaton (1998) examined the time series of future potential agricultural biomass and found reversals of trends in biomass potential. They used the climatic index of agricultural potential, CA, to reflect the impacts of several climatic change scenarios. This index was found to relate well to dry-matter productivity of a number of crops and a range of environments. They found CA increasing from present levels to doubled CO_2 levels only for more northerly stations where the benefits of warming would compensate for the increased moisture stress. However, most of the other stations generally showed declining CA with increasing temperatures to a doubled CO_2 concentration, likely because of moisture stress. Beyond the doubled CO_2 level, however, CA generally began to increase for the southern stations, but to decrease in the north. These inflection or tipping points were considered to be related to the interacting effects of summer temperature and growing season-length changes.

McGinn *et al*. (1999) developed two climate change scenarios based on the Canadian Global Climate Model daily outputs for ten years for a doubled CO_2 period. They used the EPIC (Erosion Productivity Calculator) to estimate crop yield changes and found increased yields, partly because of the fertilization effect of CO_2 and earlier seeding. The area suited to cool season crops decreases and expands for warm season crops. Both McGinn *et al*. (1999) and Gitay *et al*. (IPCC 2001) warn that grain yield predictions are sensitive to the crop model, climate scenarios, and various assumptions used and can result in markedly different results. Easterling *et al*. (2007) summarized many crop yield studies spanning a wide range of precipitation changes, carbon dioxide concentrations, climate variability, and adaptation for mid- to high latitude wheat production (Figure 39). They showed yield increases for about the first 1 to 3°C temperature increase, then yields drops for further increases. For a mean local temperature change of about 5°C yields drop below normal even with adaptation considered. The yield of warmer season crops, such as maize, does not decrease as rapidly, but the yield appears to fall at smaller temperature increases. For cropping areas dependent upon rain (*i.e.*, not irrigated) yield begins to fall below average after about a 2°C increase and is almost 25% below normal at an increase of 4°C. As found with earlier yield estimates by Williams *et al*. (1988), yield decreases become more pronounced with greater temperature increases.

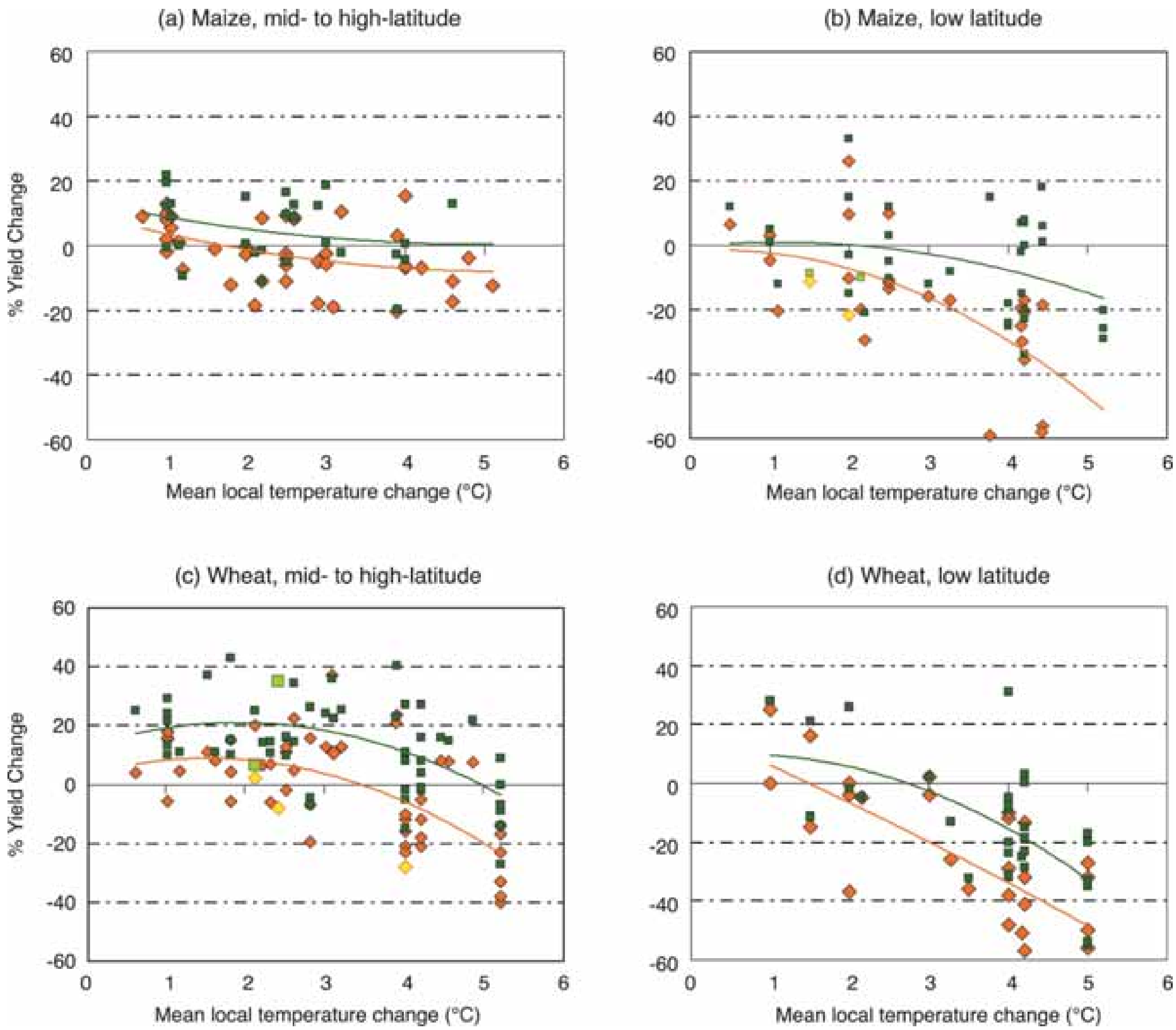


Figure 39. Sensitivity of cereal yield to climate change for maize and wheat. Responses include cases without adaptation (orange dots) and with adaptation (green dots). The studies on which this figure is based span a range of precipitation changes and carbon dioxide concentrations, and vary in the representation of future changes in climate variability. Lighter-coloured dots in (b) and (c) represent responses of rain-fed crops under climate scenarios with decreased precipitation. (Easterling *et al*. 2007) Figure TS.7

Higher air temperatures can reduce the maturity time of spring wheat and result in a yield loss of 20% (Laurila 2001). Adaptation by earlier seeding showed improved yields because of avoidance of the impacts of higher temperatures and later season droughts (McGinn and Shepherd 2003). The percentage change in winter wheat yield compared with baseline climates showed a slight decrease in yields, but an increase with CO_2 fertilization (Thomson *et al*. 2005 cited in Cutforth *et al*. 2007). Ziska *et al*. (2007) and Tubiello *et al*. (2007) also describe these and other biotic and abiotic uncertainties in the prediction of crop yields and call for improved predictive capacity. Ziska *et al*. (2007) agree that model projections of future food supply may have significantly over-estimated future yields.

The warming during 1980 to 2002 may be considered a harbinger of future effects. This change has very likely offset some of the yield gains from rising CO_2, technological advances and other climatic factors for global yields of the six main crops (Lobell *et al*. 2007). The negative impact of climate warming was found to be most significant for wheat, maize and barley.

Cline (2007) used two types of crop models (Ricardian statistical economic and process-based agronomic types) to estimate future agricultural impact by major regions, including Canada. Results for Canada for changes in agricultural potential ranged from -2.2% (without carbon fertilization) to 12.5% (with carbon fertilization) by 2080. They also warned that these and other estimates are probably optimistic as they do not account for increased losses due to insects, more frequent extreme weather events such as severe droughts and floods and increased scarcity of water for irrigation, for example. Other studies may have over-estimated the positive impact of carbon fertilization on future yields and the positive impact of adaptation.

Note that simulations of crop production including adaptations have shown the potential of measures to offset negative effects on agriculture, but often make very positive assumptions about the capability to find and use the new technology and its effectiveness,. Another weakness of many crop models is the common assumption of the use of best management practices and the omission of the effect of weeds, insects and diseases (*e.g.* Chipanshi 2005). These omissions are also research gaps.

In summary, estimates of climate change impacts on crop production are wide ranging and uncertain and depend on many assumptions including farm-level adaptation (*e.g.* crop type, seeding dates, fertilization, irrigation) and climate scenario (Lemmen and Warren 2004). They also require further integration of many other factors, such as insects, diseases, and weeds. Even with some beneficial changes, if the rates of change are faster than producers have experienced, they may pose more difficulties for adaptation. For example, new crops or livestock types may become possible, but producers have invested in machinery and learning that may not be suitable for these changes. The speed of change is important and a faster rate than previous means a more rapid rate of adaptation is needed, including policies to help deal with climate change impacts. The future rate of change is expected to be faster than any in the past 10,000 years (*e.g.*, Backlund *et al*. 2008).

Pulse crop production, future climates and adaptation: A case study

Pulse crop acreage in the Canadian Prairie Provinces increased at an average annual rate of 30% between 1978 and 1999 (SAFSB 2000). The area sown to pulse crops in the northern plains has accelerated in the last twenty years, especially in the semiarid regions where dry pea, chickpea, and lentil are used to extend the traditional wheat-fallow crop rotations (Cutforth *et al*. 2007). Climate warming has already had a significant impact on the rapid increase of pulse crop adoption in the Northern Plains.It appears to be a useful adaptation to warming climates; pulse crops are being used to a greater extent to deal with climate risks and provide other benefits, *e.g.* diversification (Cutforth *et al*. 2007).

Yield relationships across climatic gradients give useful information about the sensitivity of pulse crops to climate parameters during critical growth periods and the thresholds or climatic limits to yield (Table 3). Research needs include enhanced identification of suitable cultivars and agronomic practices (Miller *et al*. 2002).

Table 3. Comparison of equation parameters for regression models of pulse crop yield on climatic parameters (rainfall and average maximum temperature during critical growth periods; Miller *et al*. 2002)

Crop	No.[1]	Best fitting model	X range[2] mm and °C	Y range kg ha^{-1}	P	R^2
Dry bean	28	*Y* = -4 800 + 7.1 Rain§ + 200 x Tmax¶	25–300; 20.5–28.9	80–3 250	<0.01	0.53
Chickpea	37	*Y* = 2 530 - 20.7 x Rain + 0.086 x Rain^2	37–254; 20.5–29.4	290–3 400	<0.01	0.28
Soybean	20	*Y* = 710 + 4.4 x Rain	25–324; 23.3–31.4	240–3 200	0.02	0.27
Dry pea	47	*Y* = 1 600 + 4.9 x Rain	52–310; 19.3–26.1	260–4 120	0.03	0.09
Lentil	47	*Y* = -19 500 + 1 790 x Tmax - 39 x Tmax^2	52–259; 19.3–27.3	50–2 260	0.22	0.07

[1] Number of location-years used in the regression analyses.
[2] For each crop, the first range of values indicates total rainfall received during the critical growth period (mm) and the second mean daily maximum temperature during the critical growth period (°C). The critical growth period was decided independently for each crop and location, based on seeding date, to encompass the postanthesis crop development stage. Most often, the critical growth period was defined as 1 June to 31 July for dry pea and lentil and 1 July to 31 August for chickpea, dry bean, and soybean.

Dry bean yield was most strongly related to both mean rainfall and mean maximum temperatures. Dry pea showed only a weak relationship with rainfall. Soybean production is currently constrained mainly by long season maturity requirements. Increasing degree-day amounts will enable soybean production to shift northward into Saskatchewan. This wide variability in crop yields demonstrates that the optimal fit for different pulse crops in the northern Great Plains is not well known and is a research gap. Yield performance, of chick pea, for example, is likely compromised by inadequate knowledge of best management practices and lack of well-adapted cultivars.

Yield is more sensitive to changes in growing season precipitation than maximum temperature for all pulse crops, except dry bean and lentil. Dry pea and chickpea are suitable crops for dry conditions as they have high water use efficiencies, similar to spring wheat (Hatfield and Karlen 1994). Water use efficiency (WUE) is an extremely important consideration for crop production as it is the main limiting factor to crop production in the Great Plains (*e.g.*, Farahani *et al*. 1998). WUE is the dry matter grain yield divided by soil water depletion plus the total sum of precipitation between pre-seeding and post-harvest sampling dates. The mean WUE of dry pea is similar to spring wheat and the WUE of all other pulse crops appears to be lower than spring wheat. Dry bean and soybean have the lowest mean and range of WUE. Dry bean and soybean are generally not yet suitable for dry-land cropping in semiarid regions of the northern Great

Plains because of their growth timing in the mid to late summer season when peak evapo-transpiration demand is expected to occur and expand northward. Cool-season pulse crops have a good fit for the climate of the northern Great Plains, but pulse crop cultivars suited to the cool semiarid northern Plains are lacking and an improved understanding of best management practices for pulse crops is needed.

Soybean may become another possible new crop with climate change in Saskatchewan. Water-use efficiency of soybeans is projected to increase between 50-60% under doubled CO_2, but to decrease with increasing temperature (which has negative effects on crop production for semiarid climate (Allen *et al*. 2003 cited in Cutforth *et al*. 2007, Phillips *et al*. 1996, Yu *et al*. 2002 cited in Cutforth *et al*. 2007). Small savings of evapo-transpiration because of stomatal closure would be considerably offset by increases in evapo-transpiration due to higher temperatures. This effect could increase the total amount of water needed for crop production.

Temperature limits for the yield of chickpea are those exceeding 30 to 32°C. These high temperatures tend to hasten maturity and/or decrease seeds/plant and seed weight, thus limiting yield (Wang *et al*. 2006, Harris 1979). Chickpea can tolerate higher temperatures than field pea during flowering. Lentil has poor tolerance for high temperatures especially at flowering and pod set. Chickpea and lentil cultivars are suited to climatic extremes of frost and drought, for example, as they have indeterminate growth habits and require physiological stress (by drought, for *e.g.*) to terminate flowering and induce seed set (SK Pulse Growers 2000). Chickpea, dry pea and lentil (at Swift Current) use less water than spring wheat (Angadi *et al*. 1999). The mean water use efficiency of dry pea is usually similar to spring wheat, whereas all other pulse crops generally have lower WUE than spring wheat (Angadi *et al*. 1999, Miller *et al*. 2002a, Siddique *et al*. 2001). Because water stress induced acceleration of senescence cannot be stopped, short periods of water stress during seed filling are very limiting to yield.

Adaptation

The matching of agricultural activities to the environment to maximize production is even more important with a more rapidly changing climate. The highly variable amount and timing of precipitation is the most limiting factors for agriculture in Saskatchewan (Padbury *et al*. 2000) High growing season moisture deficits result from large evaporation demands compared with precipitation amounts.

Early spring seeding can improve crop productivity by avoiding the adverse effects of mid to late summer high temperatures and droughts. The risk of not reaching maturity will be lessened by a longer growing season (Miller *et al*. 2002). They examined the sustainability of pulse crops in the northern Great Plains with a focus on the growth and yield response to temperature, water, and other climate restrictions that determine their current geographic area. They considered the resilience of pulse crops to present extremes, including drought, excess water, hot and cool periods, and early frosts. Adaptation strategies discussed include earlier seeding, use of winter pulses, crop sequencing in rotations, and altering the microclimate.

Pulse crops are considered to be able to play an important role in diversifying cropping systems in the northern Great Plains. Diversification is an important step toward increasing the profitability and sustainability of agriculture (Hatfield and Karlen 1994).

Cutforth *et al*. (2007) compared the productivity and rotational effects of the five major pulse crops in the northern Great Plains. They examined the resilience of pulse crops to current weather extremes such as drought, excess water, heat, cool weather during grain filling, and early frost in order to explore effects of future climates. Accelerated crop growth and total crop failures caused by increased occurrence and magnitude of weather extremes are expected. Adaptation strategies needed to cope are suggested including earlier seeding, use of winter crops, crop rotations, and adjustments of microclimates (*e.g.* direct seeding). Technologies that increase the WUE of crops and cropping systems are needed.

Early spring seeding will improve dry pea productivity in the Canadian semiarid prairies (Johnston *et al*. 1999 cited in Cutforth *et al*. 2007). Management practices can enhance early seedling emergence, prolonged reproductive period, and increased pod fertility. Some of the current operational adaptation methods include tillage methods. No-till management and the resulting standing stubble are important for improving available water for crops by snow trapping, reducing wind speeds and evaporative demand for water and protection against soil erosion (Cutforth *et al*. 2007). The increased drought and intense rainfall events expected with climate change will require even greater soil erosion conservation.

In conclusion, pulse crops appear to have enormous potential for improving adaptation to climate change by increasing the sustainability and diversity of wheat-based dry-land cropping systems in the northern Great Plains (Miller *et al*. 2002). Diversification for both production and markets can be a useful strategy for adapting to a changing climate. Diversification can be achieved by including pulses into the cropping system and by adding both cool- and warm-season crops (Cutforth *et al*. 2007). Pulse crops appear to be a suitable strategy for dealing with climate change because of their drought and heat tolerance, efficient water use, and moisture-conserving growth habits. The relative advantages of different pulse crops, best management practices, and key production risks, however, require further research as they are not fully characterized.

Extreme Weather and Climate Events: Droughts and Floods

In recent years, consecutive severe droughts, early frosts, flooding, and other extremes have challenged agricultural production in the prairies. Under a changing climate, the frequency of both drought and severe flood events are expected to increase. More specifically, all Global Climate Models project future increased summer continental interior drying and associated risk of droughts (Watson *et al*. 2001). The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2007) concludes that future increases in the area affected by drought are likely (*i.e.* 66% probability of occurrence). The area of very dry climate has doubled since the 1970s and much of the Canadian Prairie Provinces has exhibited this drying (Dai *et al*. 2004). The frequency of heavy precipitation events will very likely increase in the future (90-99% probability) (IPCC 2007).

Changes in the frequency, area, intensity and magnitude of extreme climate events, is an important consideration for Saskatchewan's agriculture. Droughts, floods, and heat waves have the potential to offset the beneficial effects of moderate increases in temperature, growing season and CO_2. Agriculture in Saskatchewan and elsewhere has been subjected to many severe climate events in the past decade, raising concerns about its future capacity to cope with a more variable and changing climate (SSCAF 2003, Wheaton *et al*. 2005, 2008). This section focuses on droughts and floods as they are among the most hazardous of the extremes.

Droughts

Prairie drought is Canada's most costly natural hazard. Globally, "More intense and longer droughts have been observed over wider areas since the 1970s…Increased drying linked with higher temperatures and decreased precipitation has contributed to changes in drought" (IPCC 2007:8). Observed changes in drought show that some of the projected changes are already occurring. Droughts have shown an increase in intensity and duration since the 1970s globally (Dai *et al*. 2004). Heat waves have also increased in frequency with more extreme warm nights and days (Vincent and Mekis 2006). Evidence that drying is already occurring is apparent from declining water levels in many closed-basin prairie lakes (van der Kamp *et al*. 2006) and declining levels of surficial aquifers in the Prairies (Wittrock 2005).
Southwest Saskatchewan and southeast Alberta have the lowest annual precipitation and highest coefficient of variability of precipitation in the Prairie Provinces. Southern Saskatchewan also has the highest average annual hours of sunshine, the largest number of days with high temperatures (maximum above 30°C), and the highest average daily wind-speeds (Wheaton 1998). These factors and others combine to give this area the greatest risk of droughts in Canada and among the greatest in North America.

Wetherald and Manabe and (1999) and Sheffield and Wood (2007) are among the first to examine changes in drought under future global warming. The latter work analyzed soil moisture and drought characteristics over global land areas, except Antarctica. They considered uncertainty in regional climate change by using data from many models and for three future emission pathways. The climate models replicate the occurrence of large area drought fairly well, but over-estimate droughts longer than a year. They find decreases in soil moisture globally for all scenarios, with a doubling of the area of severe soil moisture deficits and the frequency of about half year droughts from the 1950s to the 2090s. The regional time series of frequency of short term droughts shows a steeper increase through time for Western North America as compared with changes elsewhere.

Wang (2005) estimated future changes in soil moisture and found consistency in 15 GCM projections of summer dryness and winter wetness for the northern middle and high latitudes. The average of all the models showed a signal of decreased soil moisture, despite the increases in annual precipitation. The primary mechanisms operating to increase drought frequencies are decreasing precipitation and increasing evaporation driven by increasing temperatures and longer warm seasons. These results are consistent with several others that estimate drying over the interior of northern hemisphere continents over the next century, especially in summer (*e.g.* Wetherald and Manabe 1999, Gregory *et al*. 1997, Burke *et al*. 2006, Cubasch *et al*. 2001, Kharin and Zwiers 2000).

Increasing wind speed is a factor in increasing evapo-transpiration and causing water stress to plants because of lower plant available soil moisture and higher transpiration rates. High wind speeds also cause structural damage to crops and property. Although scenarios of future changes in wind speed are few, Barrow *et al*. (2004) projected increases in the order of 5-10% for the 2050s across the prairies, with the largest increases in the winter and spring. Mid-latitude westerly winds have already strengthened and moved pole-ward in both hemispheres since the 1960s (Solomon *et al*. IPCC 2007).

Bonsal and Regier (2006) provide more regional assessments of future drought over southern Canada using the Standardized Precipitation Index (SPI) and the Palmer Drought Severity Index (PDSI). The SPI is indicates little future change in droughts, as it is a simpler index that considers only precipitation. The PDSI is more complex as it incorporates a water balance approach using precipitation, potential evapo-transpiration, antecedent soil moisture and runoff. It shows that drought increases dramatically in both spatial extent and severity with the effect of increasing temperatures. Future droughts may frequently exceed the worst droughts on record, including those of the 1930s and early 2000s.

Floods

Excessive rainfall and flooding result in large damages for agriculture and communities, including: delayed spring planting, crop losses (both quality and quantity), soil compaction (with use of equipment on land), runoff and soil erosion, reduced access to land, and harvest constraints. Social impacts of floods include changes in quality of life, damage to infrastructure, tourism and recreation and uncertainty of public policies (Kulkarni 2002).

Saskatchewan has among the most extreme rainfall events in Canada. For example, the largest eight hour precipitation event in Canada occurred in the Vanguard area of southwestern Saskatchewan on 3 July 2000. Damage included flooded buildings, washed-out roads and rail lines, compromised drinking water supplies, and decreased agricultural production (Hunter *et al*. 2002).

Wittrock *et al*. (2008) reported many disruptive and costly flood impacts in prairie communities in recent years, including flooding of homes and businesses, compromised drinking water supplies, damaged roads, and overwhelming the capacities of emergency services. These examples indicate the type of damage expected to occur more frequently with climate change, unless preparedness and adaptation is improved.

Changes in land suitability and northward shifts

Although few authors have examined changes and geographic shifts in land suitability, enough results are available to give a flavor of possible impacts. Weber and Haer (2003) examined impacts on agricultural land values in the Prairie Provinces and found significant gains in land values. These increases are a result of the increase in growing season length providing suitability for more valuable crops. They did not consider, however, various projected changes in seasonal and extremes of precipitation and specifically drought. The Land Suitability Rating System

(LSRS) was used to investigate the changes in land rating under future climate scenarios (Nyirfa and Harron 2001). Much more severe moisture limitations, especially for spring-seeded small grain production, were found under future scenarios in the southern prairies with drier and longer growing seasons. Sauchyn *et al*. (2005) determined that the area with an aridity index in the semiarid to dry subhumid category expands by 50% with warming. Hogg and Bernier (2005) found that southern areas of the current boreal forest are expected to come under further drought stress in the 2050s. Climate change could result in northward migration of crop production (Smith and Almaraz 2004) where soil and landscape conditions permit.

Chen *et al*. (2008) calculated changes in climate indices and agricultural land suitability for spring-seeded small grains (SSMG), canola and corn crops across Canada. They used three GCMs and the IPCC A2 and A1B emission scenarios. They found that most of the prairie region remains similar to 1971-2000 average aridity levels or improves slightly, depending on the GCM. This reflects the increase in spring precipitation (March, April and May) combined with an assumption of earlier crop seeding and maturity dates which avoid the increasing aridity expected for the summer months (June, July, and August). Land suitability results indicate substantial increases for SSMG and canola, especially north of current agricultural region (Chen *et al*. 2008) where soils permit. Increasing heat may reduce suitability for canola crops as compared with SSMG, especially in southwest Saskatchewan. This would require the development of canola (and other sensitive crops) with increased heat tolerance during the flowering period. Agricultural production could expand northward, where soil, landscape and socio-economic factors are not limiting. The potential also exists for the northward expansion of warm-season crops, such as corn and soybeans, with the similar limitations.

The improved soil moisture conditions in the earlier cropping season projected by Chen *et al*. (2008) did not consider the effects of extremes, such as increasing droughts, hot spells, and large and or intense rainfall events and assumed the use of appropriate adaptation measures, specifically earlier seeding and harvest Earlier seeding, expansion of higher value low-residue crops, and production shifts northward and/or onto rangelands could potentially increase the risk of soil erosion. Further enhancement of soil and water management and conservation may be required to prevent degradation and to sustain agriculture (Sauchyn 2007). Other warnings include the need to consider the increased and/or new pest and disease pressures on crops (and livestock).

Livestock Production, Management and Future Climates

The livestock industry is important to Saskatchewan and Canada. Saskatchewan has almost 30% of the Canadian beef cow herd and is a major exporter of feeder cattle. The province produces more than $1 billion of beef annually and is the second largest beef producing province in Canada (Government of Saskatchewan 2008). In 2008, the number of cattle and calves on Saskatchewan farms was 3.385 million (Saskatchewan Ministry of Agriculture 2009).
Little research has been done on the effects of climate change on livestock production (Sykes 2008, Sauchyn and Kulshreshtha 2008). Extreme weather (*e.g.* hot spells, scarce and poor quality water, blizzards, ice storms) affect the comfort, productivity and reproduction of livestock. Illness and death of prairie livestock are related to hot spells and poor quality water, for example. Indirect effects occur through weather and climate effects on feed, insects and diseases.

Sykes (2008) and Cohen *et al*. (2002) provide perhaps the only estimate of climate change effects on forage and cattle production in the prairies. Sykes' (2008) approach was progressive as it addressed the impacts of climate change on several integrated aspects of the forage-cattle system, including many agro-climatic variables, soils, plants and animals in a single decision support model, "GrassGro", a decision support tool for forage and livestock (sheep or cattle) production based on site-specific climate and soils data (Moore *et al*. 1997).

Sykes (2008) used the GrassGro DST to simulate the effect of climate change on intake and production of steers grazing on grass pastures at Melfort and Saskatoon, Saskatchewan. Three common climate models (CGCM2A21, HadCM3A21, and CSIROMk2B11) provided daily data for three standard future time periods. The pastures used were crested wheatgrass and hybrid brome grass and the steers were assumed to be medium frame British breeds (mature weight of 500kg). Several other specific assumptions were made regarding time on pasture and supplements. They concluded that the productivity of grazing livestock would continue to be greater at Melfort than at Saskatoon, and hybrid brome grass would be better suited to future climate changes than crested wheatgrass for both locations. A limited set of adaptations including a specified stocking rate and single grazing period were tested. Other adaptations showed improved average daily weight gain of steers, but at the expense of a lower carrying capacity, increased use of supplements, and/or reduced grazing season. Supplemental feed requirements increased during each of the three future time periods at the Saskatoon site.

In summary, climate change has the potential to affect livestock productivity directly, through thermal and water stress, and indirectly through effects on feed, insects and diseases (Backlund *et al*. 2008). Thermal stress reduces productivity and conception rates and is potentially life threatening to livestock. Increasing temperatures enable the spread of animal diseases (and weeds) from south to north, resulting in new possible threats. Livestock production may be reduced in summer months because of heat stress and feeding challenges, but this may be partially offset by the advantages of a warmer and shorter winter.

The assessment of climate change impacts on livestock production in Canada is a critical research gap. Impacts must be explored in order to suggest and test appropriate and effective adaptation strategies to avoid negative impacts and take advantage of positive effects.

Insects, Diseases, and other Pests

"*Drought, plant or livestock disease and pest infestations have moderate to severe impacts on agricultural productivity throughout the Canadian Prairies. These challenges present serious problems not only for the individual farmer, but also to provincial and national economies*." (Powell *et al*. 2007: 73)

Climate affects crop and livestock production indirectly through effects on disturbances such as insects, diseases, invasive species, fire, and wind damage. This section focuses on information for selected insects and diseases, although several other pests, such as weeds and rodents also cause major problems for agriculture and should be also be assessed. Research regarding the relationship of diseases, insects, and other pests and changing climates in the prairies and elsewhere is rare.

Many insect pests are currently limited by winter conditions and relatively short cool summers. Warmer winters and longer summers may result in more suitable conditions for insects, diseases and other pests. A warming climate also results in improved prospects of new invasive species and changes in the abundance of beneficial species (pollinators and natural predators). Key insect species respond positively to heat, especially warmer spring conditions, and forecasts of expected range and risks should be constructed to better prepare effective management plans.

High numbers of grasshoppers plagued much of agricultural Alberta and western Saskatchewan during the drought of 2001-2002 (Wittrock 2005). The grasshopper forecast risk maps for a current year are based on adult grasshopper densities of the previous summer. The grasshopper counts of summer 2002 showed severe to very severe risk for much of western agricultural Alberta and severe risk for about a third of agricultural Saskatchewan (Johnson and Calpas 2003, Saskatchewan Agriculture, Food and Rural Revitalization 2002). Other pests benefited from the drought conditions. Besides grasshoppers, considerable damage resulted from flea beetles, cutworms, and gophers in 2002 (SK Agriculture, Food and Rural Revitalization 2002 cited in Wittrock 2005).

Above a minimum temperature, the growth rate of grasshoppers increases non-linearly up to a maximum temperature (Powell *et al*. 2007). High precipitation amounts tend to reduce potential grasshopper populations, especially in the spring. Cool, wet weather in the spring and warm, dry fall and early winter weather are strongly linked with low grasshopper populations.

Unfamiliar insects such as cereal leaf beetle, seedpod weevil, and swede midge could become an increasing concern for farmers in the future. Farmers have confronted new insect pests in the past associated with diversification into new crops. Weis (Ewins 2009) points out that climate change presents a new and more serious challenge by altering dynamics of the insect populations, including time of emergence, development, reproduction rates, activity and feeding patterns, and reducing winter mortality. New insects may invade and thrive, but some existing insects may be reduced or disappear. The nature of the future insect problem is difficult to anticipate. Enhanced monitoring, modeling, predictive ability and new insect control methods are required.

Insects, weeds, and diseases are predicted to spread pole-ward with the shifting climate zones. Many of the world’s worst weeds are C4 plants and these are expected to gain advantages in crop-weed competitions with increasing CO_2. Longer and warmer summers and milder winters lead to higher survival rates, more generations, greater activities and therefore higher risks of damage. Changing wind-speeds mean changed spore and insect transport (Smith and Almaraz 2004).

Archambault *et al*. (2001) is one of the few studies to examine weather and climate influence on the effectiveness of herbicides and pesticides. They found a varied response and that the interactive effects of increased CO_2 and temperature may cause a decrease in herbicide efficacy in about fifty years in Saskatchewan.

In the case of vector-borne livestock diseases, temperature, rainfall, and humidity are the major climatic factors of transmission (McCarthy *et al*. IPCC 2001). The recent outbreaks of anthrax are examples of the relationship between rainfall, drying and cattle deaths (Epp personal comm. 2009).

Some vectors of disease for both humans and livestock benefit from warmer conditions. The Culex tarsalis mosquito, the main vector for the West Nile virus (WNv) in the Canadian Prairies, is a good recent example (Curry *et al*. 2007). This mosquito species and the WNv do especially well in rural habitats, so are an important threat in agricultural regions for humans, horses, birds and other animals. In 2003 and 2007, Saskatchewan and other Prairie Provinces and Great Plains states experienced severe outbreaks of West Nile virus (WNv). In both years, WNv activity and human disease were more prevalent in the southern, grassland eco-region of Saskatchewan, with 947 human cases and seven deaths reported in 2003, and 1,456 cases and six deaths in 2007. This eco-region has the highest numbers of the mosquito, Culex tarsalis, the largest area of available larval habitat for this species, the warmest temperatures and the longest frost-free period. Many factors drive the risk of acquiring WNv infections, including temperature and precipitation patterns, eco-regions, urban/rural landscape, mosquito control programs and person protective behaviors. Contrasting climate patterns appear to be the major factors in determining high and low risk years. Climate change is expected to bring many advantages for the mosquito and for the risk of WNv and other diseases it may carry (Wheaton *et al*. 2009).

Human health in both rural and urban areas is affected directly and indirectly by climate change and must be considered as an aspect of adaptive capacity. Morris and Wheaton (2008) evaluate the capacity to address illness related to global warming in Saskatchewan. Several of these health concerns would be relevant to people living and working in agricultural regions, including heat stress, vector- and water-borne diseases, cardio-respiratory conditions, and skin cancer. They outline methods for evaluating the current capacity of health-related systems to address increased rates of illness that are likely associated with continued global warming.

Climate change has many implications for pests and diseases and they are a major challenge for agriculture. The effects of climate change on pests, weeds and diseases and their combined effects are rarely included in assessments of the impacts of climate change on agricultural production and this is an important weakness to be addressed (Hatfield *et al*. 2008, Wheaton and Kulshreshtha, in press).

More about Future Adaptation

Adaptation measures to reduce negative impacts and enhance opportunities for agriculture and its competitive advantages are of fundamental importance to Saskatchewan, Canada, and the world. Adaptation to a changing climate and adaptive capacity have only had cursory attention for Saskatchewan sectors, and agriculture has had most attention and earliest (*e.g.* Wheaton *et al*. 1992, Williams 1988), but still has many unknowns. Adaptation takes place in many forms including prevention, avoiding negative impacts, transfering impacts, etc.

Agribusiness companies are aware of the risks posed by weather and implications for adaptation. For example, Viterra's (2009) 2008 annual report states: "Viterra's most significant risk is the weather. The effects of weather conditions on crop quality and production volumes present significant operating and financial risk to Viterra's Grain Handling and Marketing segment … Weather and moisture levels are a determining factor in crop selection by producers at seeding time, the variety of seed sown, and the amount of proprietary seed purchased."

Federal and provincial governments have responded to the impacts of extreme climatic events such as droughts with safety net programs to offset negative socioeconomic impacts (Wittrock and Koshida 2005). More recently, provincial drought plans are being developed and improved and national drought planning is underway (Wheaton *et al*. 2007).

Drought also results in an accumulation of stressors that can change an emotionally healthy person to one experiencing severe stress (Imhoff, p. com. 2003). More intense, larger, and longer droughts will be expensive and difficult challenges to policy and subsequent programming. This is a motivation for the further development of drought preparedness with such programs as the Drought Early Warning System (Canada DRI 2009) and the Drought Preparedness Partnership and Program (Lee p. comm. 2009). Some coordination for North American Drought Monitoring (*e.g.*, NADM 2009) is taking place and requires enhancement.

Programs for enhancing major agricultural adaptation programs, research, awareness, linking of science with policy, and measures, such as irrigation and soil and water conservation, are priorities. Soil conservation not only improves the soil resource and drought coping, but it can contribute to mitigation by the storage of carbon. The Permanent Cover Program (Vaisey *et al*. 1996) and the Pasture Program have reduced sensitivity to drought and flood effects over large areas. Irrigation techniques have improved using more efficient and effective systems and matching water application to need (Stratton *et al*. 2006). Vulnerabilities to water scarcity continue to be exacerbated by such factors as the major use of water for irrigation, other non-agricultural uses and losses from reservoirs and open channels.

Agricultural land use in Saskatchewan is undergoing rapid transitions. The question of how farming will change in the future and what this means for adaptive capacity must also be addressed to help estimate possible impacts. Literature on the future of farming in Canada and Saskatchewan is scarce. Information on future farm trends would be useful in assessing the nature of adaptive capacity, however, this information is scarce. Wheaton *et al*. (2005) document more than 25 past trends and near future possible farm trends of relevance to the development of water conservation guidelines. The clearest and most dominant of these trends are likely to continue over the next few years, including increased farm size, decreased number of farms, and aging of farm operators. The likely rate of change, however, appears to be unknown or not estimated.

Bradshaw (2007) urges the consideration of primary agriculture's current trajectories in impact assessments. These trends include increased output productivity among individual operations, larger and fewer farms, more specialized production on individual farms, more intensive production on individual farms, greater integration of farms into the agri-food system and more "pluriactivity" among individual producers and their families.

Kulshreshtha and Noble (2007) discuss four main changes in farming: decline in total area of spring wheat production; decrease in summer-fallow area; a corresponding increase in the production of other corps; and an increase in livestock operations. The changing agricultural economy has resulted in several modifications, most notably, the decrease in the number and increase in the size of farms. Another change is the changing role of the family farm and the growing influence of agribusiness in the farm economy. They address the role of government policy in agriculture and note that federal government policy instruments have included intervention measures, such as market regulation, income stabilization and grain transportation subsidies. “The federal and provincial governments support Saskatchewan agriculture through operating, capital and program-specific expenditures. Average annual government expenditures between 1999 and 2002 were estimated at $1.3 billion, almost a quarter of the value of farm cash receipts (excluding government payments). Thus a good part of the agricultural economy depends, either directly or indirectly on government support ... Because of high capital investment requirements, farms will be even more vulnerable to market fluctuations in the future and the adoption of enhanced risk management strategies will be the key to their survival … Policy instruments at all levels of government have played a role in determining past land use, and will continue to do so in the future.”

The next parts of this section give more specific examples of adaptation measures, such as irrigation, awareness, and research.

Information and awareness

Information and awareness are critical first steps to to deal with climate change impacts more quickly and appropriately. Enchanced adaptive capacity of agricultural producers and policy makers includes the knowledge and skills to expand the array of suitable and effective options available to them. Moth and Baier (2005) recommend aggressive research and caution that complacency is very risky.

The role of institutions in adapting to climate change includes the development and implementation of comprehensive support mechanisms that improve the capacity of different sectors to adapt (Diaz and Gauthier 2007). This goes beyond disaster preparedness, the introduction of new crops, and reducing the exposure of institutions to the ability to be aware of, identify and anticipate problems, seek solutions, and implement the solutions in fair, efficient and sustainable ways and to perform functions that facilitate the adaptive capacity of their constituencies. Adaptive capacity goes well beyond access to resources and technological solutions.

Awareness of risks and opportunities related to climate change is a key aspect of adaptation (Reid *et al*. 2007). People and institutions who consider that climate change is irrelevant to them are not likely to adopt adaptation measures and reap the benefits. Government agencies are important sources of information and providers of safety net programs for adaptation and current risk management instruments, such as crop insurance.

Irrigation

Increased irrigation is a commonly used and important adaptive strategy to deal with droughts and a drying climate. Irrigation was a vital adaptation strategy during the severe drought of 2001-2002 and would likely continue to be increasingly important with continued climate change (Wheaton *et al*. 2007). Nemanishen (1998) states that "There is no technology, apart from irrigation, which can sustain either cereal grain or hay production during extended drought periods in the Palliser Triangle." However, expansion of irrigation will require considerable investment and also will increase agricultural consumption of water (which is already large) and energy.

Irrigation use will continue to be stressed by climate effects on water availability in the future. The competition between agriculture and other uses will increase (*e.g.* Motha and Baier 2005). The demand for water for irrigation and livestock is expected to rise with increasing temperature and expansion in these sectors (Sauchyn and Kulshreshtha 2008). Irrigation water is expected to become less available, however, and agriculture may have to adapt to rely more on dry-land production (Cutforth *et al*. 2007).

Research

Many research gaps are described in previous sections and more examples are provided here. More information is needed to understand the changes in synchrony and suitability of climate and plants normally grown. "Continued research into the adaptive capabilities of current agricultural technologies and the development of future technologies will contribute to maximizing crop production in the future" (Dhungana *et al*. 2006). Adaptive technologies include: changing seasonality of production, sowing date, crop varieties and species, new varieties, water use efficiency, tillage practices and diversification (Smit and Skinner 2002, Bradshaw at al. 2003, Burton and Lim 2005, Sauchyn and Kulshreshtha 2008).

Research needs include 1) coupling of crop, climate, pest, and adaptation simulation models (Dhungana *et al*. 2006), 2) comparing suitability of breeding objectives against climate projections, 3) breeding and selection for disease resistance, and 4) cultivars assessed, chosen and tested for suitability to future climates.

As the Conference Board of Canada (Roberts *et al*. 2006:2) states, "Adaptation is not new; what is innovative is the idea of incorporating adaptation to future climate risk into policy-making… good policy necessitates an immediate, active adaptation focus" Policy implications of climate change for agriculture are briefly addressed in the following section.

Policy Implications

" *Research and policy initiatives for adaptation to climate change are relatively undeveloped for a number of reasons, including the tendency for climate change to be equated with only reduction of greenhouse gas emissions, without acknowledgement of the need for understanding adaptation to altering conditions. The Canadian agricultural sector will benefit from policy-*

relevant research that examines producers' capacity to deal with climate and weather risks" (Wall and Smit 2007:237)

The highly adaptive capacity of the agricultural sector could not have been attained without government policy at many levels (Wall *et al*. 2007). However producers are on the front lines of adaptation, because they are the first to be affected and to take action, or not. Policy is a set of guidelines, which includes ethics, economics and law agreed upon by the public through the political process. Polices are converted into government programs. Within the Canadian Constitution both levels of government have responsibility for activities within the province. Some of the responsibilities are joint, *e.g.* crop insurance, and both governments work together to develop and deliver the agricultural programs (Furtan 2005:34.)

Two of the main policy responses to climate change are adaptation and mitigation. Agriculture is responsible for the emission of greenhouse gases and has a share in mitigation. Appropriate integration of both adaptation and mitigation in agriculture is needed to ensure that they are coordinated and mutually supportive. This means that adaptation measures must be designed to generate fewer greenhouse gas emissions and to store more carbon. Mitigation measures must be designed to support and enhance adaptation.

Venema (2007) suggested that a test for agricultural policy, related to building adaptive capacity for managing climate change risks, is whether it keeps existing livelihood options open and creates new options. He recommended that payments be considered for providing ecosystem goods and services (EGS), such as building up soil conditions, which is a key aspect of improving adaptive capacity.

What is the role of programs such as the Canada-Saskatchewan Environmental Farm Plan (EFP) Program (AAFC and SAF ND) in addressing adaptation to current and future climate warming? Beneficial farm management practices, with adaptation components, may be useful in dealing with adaptation deficits and result in benefits. Best management practices enable coping with droughts and other aspects of climate change, including water well management, land management for soils at risk, cover crops, nutrient recovery from waste water, irrigation management, enhancing biodiversity, grazing management planning, integrated pest management planning, and irrigation management planning.

Wheaton and Kulshreshtha (in press) write that institutional adaptations will be required to proactively deal with impacts of climate change on agriculture. Existing policies and programs may not be adequate to meet the challenges and may need to be considerably modified. Problems with other policies may also have interactions with policies to deal with climate change. For example, Storey (2005:46) writes that the federal and provincial governments have not arrived at a stable policy for income stabilization and support, in comparison with that enjoyed by farmers in the United States and the European Union.

The policy implications of severe droughts require further assessment and adaptations as indicated by the severe impacts of the 2001 to 2002 drought that affected all of Canada, but was hardest on Saskatchewan and Alberta. Saskatchewan was the most severely affected province in 2001 with 48% of the Canadian drought-induced losses. Drought contributed to a negative or zero net farm income for Saskatchewan in 2002 (Statistics Canada 2003 cited in Wheaton *et al*. 2008).

Government response and safety net programs can offset some of the negative economic and social impacts from severe multi-year droughts, such as the 2001 to 2002 event. These programs included crop insurance, the Rural Water Development Program, the Net Income Stabilization Account, the Canadian Farm Income Program and the Livestock Tax Deferral Program (Wheaton *et al*. 2008), and Permanent Cover Program (Vaisey *et al*. 1996). The crop insurance program had very high payouts, with the highest in Saskatchewan at over $1 billion in the 2002-2003 crop year (Wheaton *et al*. 2008). Many of these programs have been changed and require further testing under severe droughts which tend to result in immense losses. Another reason for testing policies to respond to severe droughts is that droughts of this magnitude are common in records of the pre-settlement climate of the western interior (Sauchyn 2007). A drought of unprecedented duration is most likely to exceed the coping capacity of Prairie producers and agricultural institutions, and is the greatest climatic risk to the future of Prairie agriculture. Sauchyn (2007:80) concludes that "there are few existing strategies, other than government assistance, to sustain agriculture through these most extreme conditions."

Policies are developed with consideration of many other issues other than climate and too often ignore climate. Policies that successfully address the impacts of climate change must consider climate dynamics more carefully and thoroughly to facilitate successful adaptation. Many barriers to improved adaptation need to be overcome. An improved communication of science to policy analysts and makers requires fast-tracking so that they have the best and most recent relevant findings. This development requires access to suitable climate information, having the ability to use it, and using that information and expertise as a part of policy development. Smith and Almarez (2004) conclude that new and more flexible policies are needed to allow the introduction of adaptation measures such as new crops and cropping practices that are better equipped for a world affected by climate change.

Conclusion

The uncertainty of precipitation and considerable extremes of temperature and other climate events are serious risks to Prairie and world agriculture. One of the largest challenges will be conflicts over increasingly scarce supplies of water. Evidence of climate warming in the Canadian Prairies and the world is substantial, especially for about the last 50 years. Climate warming and other climatic trends will continue to have significant impacts on agriculture. Climate change implications require agriculture to adapt to ongoing fairly rapid changes. Agriculture is also expected to play a role in mitigating greenhouse gas emissions and storing carbon, amid many other challenges, including markets, and energy and food security issues. Climate change means changed variability and new geographies of production, among other issues.

FORESTRY

Introduction

The Provincial Forest (*i.e.* the managed forest) in Saskatchewan falls in the Boreal Transition and Mid-Boreal Uplands Ecozones (Figure 40). It makes up 54.5% of the total provincial land area or approximately 35.6 million hectares. Provincial Forests are managed according to the basic principles of Sustainable Forest Management (SFM) as defined by the Canadian Council of Forest Ministers (CCFM 2003). Six criteria are used to assess sustainability of forest management:

1. Biological Diversity – the variability among living organisms and the ecosystems of which they are part;

2. Ecosystem Condition and Productivity – the stability, resilience and rates of biological production in forest ecosystems;

3. Soil and Water – the quantity and quality;

4. Role in Global Ecological Cycles – the impact of the forest and forest activities on global ecosystem functions, especially the carbon cycle;

5. Economic and Social Benefits – sustaining the flow of benefits from forests for current and future generations and;

6. Society's Responsibility – fair and effective resource management choices

Periodic reviews of SFM using these criteria are done federally (*e.g.* CCFM 2005) and provincially (*e.g.* Saskatchewan Environment 2007).

Forest management in Saskatchewan is governed by the Forest Management Act of 1999 which allocates rights to harvest timber through Forest Management Agreements, Term Cutting Licences, and Timber Permits. It also stipulates how forest management plans are done and how forest industry must undertake reforestation and other aspects of forest resource conservation (Saskatchewan Environment 2007).

The Boreal Plain ecozone begins where the Boreal Shield ends and extends to the southern margin of the forest. Most timber of commercial value in Saskatchewan lies in this ecozone. The relatively warm climate and deep soils support a diverse and productive mix of pure conifer forests and extensive mixedwood forests consisting of white spruce, jack pine or black spruce mixed with trembling aspen, balsam poplar or white birch. Wetlands dominate almost half of the land base. Forests give way to grasslands where the Boreal Plain meets the Prairie ecozone, where potential evapotranspiration exceeds precipitation. Many forests in this area grow on poor sites and are frequently subject to drought, insect attack, mistletoe and fires (Hogg and Bernier 2005).

In Saskatchewan's far north lies the rocky terrain (shield) of the Selwyn Lake and Tazin Lake Uplands (Figure 40), with its expanses of lichen woodland (taiga) and peatland vegetation dominated by black spruce. White birch is the only common broad-leaved deciduous tree in this ecozone. Further south is the bedrock-controlled Boreal Shield (Figure 40), with black spruce and jack pine dominating the rocky uplands and scattered black spruce and peat in the wetlands. White birch and trembling aspen become somewhat more common with the warmer and moister climate.

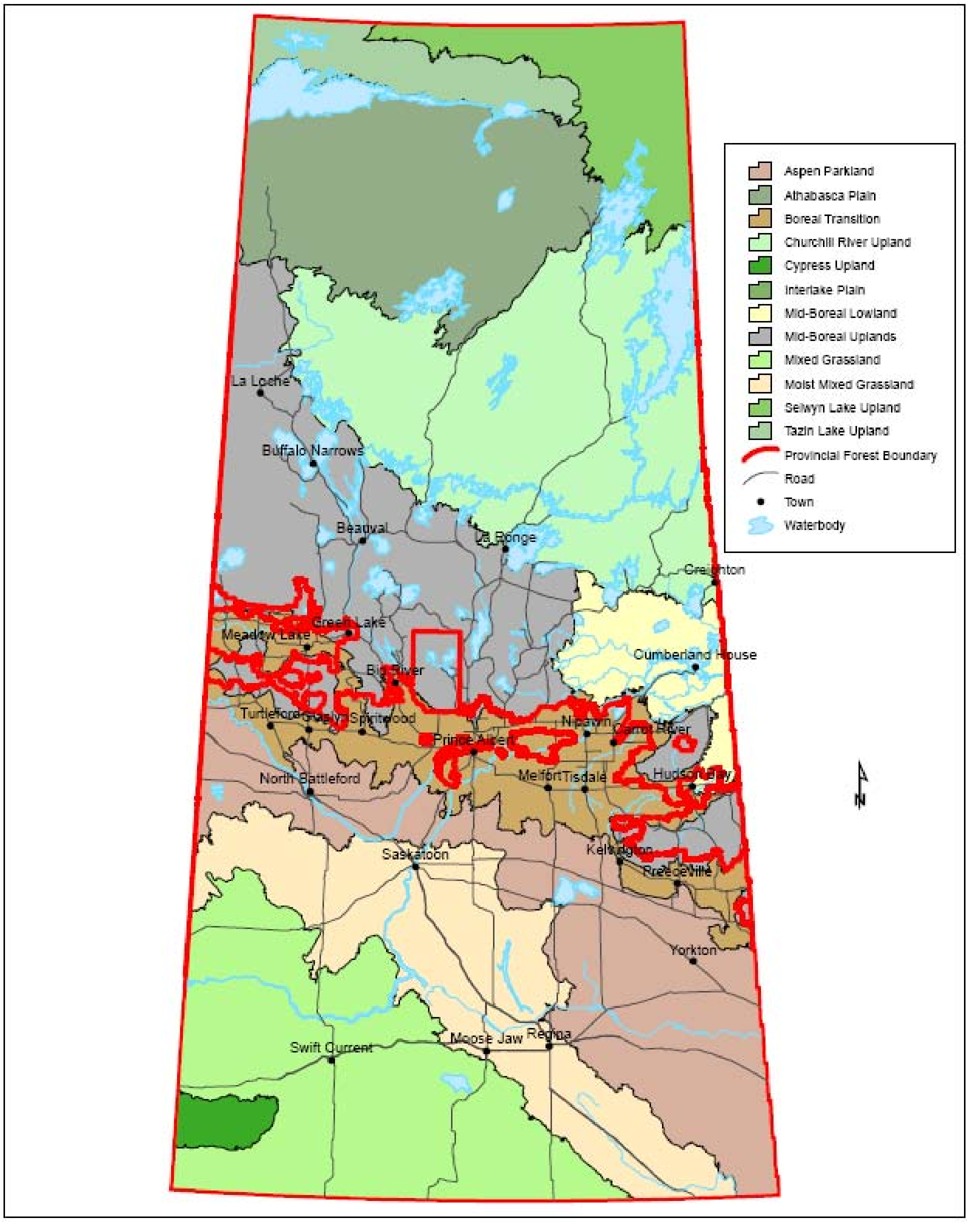


Figure 40. Map of Saskatchewan showing Ecozones and the Provincial Forest boundary (Saskatchewan Environment 2007).

The impacts of climate change on Saskatchewan Forests

Forests in Saskatchewan are already vulnerable to a range of climate and natural disturbance factors, and may be more vulnerable to climate change than other forest regions in Canada. Northern Saskatchewan occurs in the portion of Canada's boreal forest that experiences the highest rate of fire disturbance in the country, along with northern Manitoba and northwestern Ontario (Balshi *et al*. 2009). White spruce is highly vulnerable to spruce budworm and has experienced large outbreaks in the past 10 years (R. McIntosh, personal communication). Aspen has been subject to outbreaks of the forest tent caterpillar and productivity has declined dramatically in areas where drought coincided with these outbreaks (Hogg *et al*. 2005). Forest areas along the southern margin of the boreal forest are subject to droughts, fire and insect attack, and in some areas grow on sites that are marginal for supporting tree growth (Hogg and Bernier 2005). If forests are to be sustainably managed in the future, it is essential to understand the potential impacts of climate change.

The impacts of climate change can be divided into several broad categories. These include

- Changes to large-scale disturbance regimes, *e.g.* forest fires, insect outbreaks
- Changes in tree growth rates
- Changes in tree species distributions
- Changes in physical conditions that affect forest operations (harvesting, road transport, etc.)

Forest fires

Disturbance regimes in the western Canadian boreal forest are expected to change significantly. Increases in forest fire frequency, more severe fire behavior and increased area burned are expected. Parisien *et al*. (2004) projected future forest fire behavior in central Saskatchewan. Head fire intensity (HFI), a measure of the fire's energy output, was used to quantify fire behavior potential because it can be related to fire behavior characteristics, suppression effectiveness, and fire effects. Percentile HFI maps were created with fuels data and fire weather from three simulated climate scenarios produced by the Canadian Regional Climate Model (CRCM). These scenarios represent base (1×CO), double (2×CO), and triple (3×CO) levels of carbon dioxide in the atmosphere. Their results show a marked increase in fire behavior potential in a 2×CO environment, whereas little change was observed from 2×CO to 3×CO . They also found that the number of days that could support extreme fire behavior potential may quadruple in a 2×CO climate. Furthermore, fires are also expected to be more intense, on average. An increase in fire intensity would likely be translated into greater fire spread and more variable fire behavior, leading to increased area burned. However, a changing climate does not necessarily entail a ubiquitous or uniform increase in fire potential throughout an area. Parisien *et al*. (2004) found that there was significant spatial variation in the effects of climate change on HFI values, due to the interaction and spatial variation between fuel types and weather patterns.

Flannigan *et al*. (2005) used the Canadian Global Climate Model (CGCM2) and the Hadley Global Climate Model (HADCM2) to project area burned in the 2090s based on future values of the Canadian Forest Fire Weather Index. The analysis used Canadian Ecozones as the unit of analysis. Figure 41 shows the results with CGCM2, while Figure 42 shows those from HADCM2.

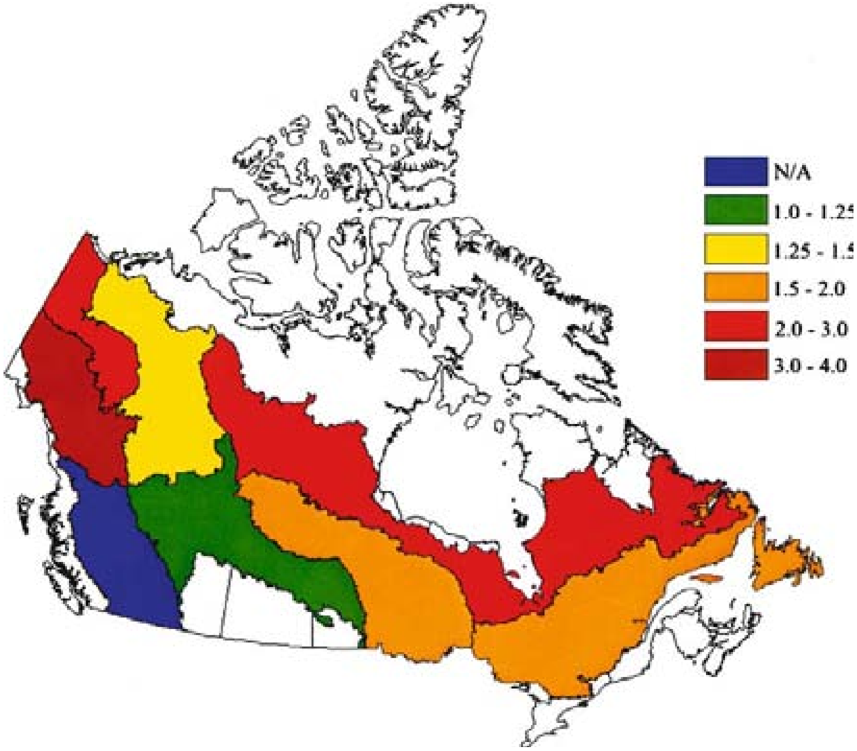


Figure 41. Increases in area burned by ecozone based on projections from CGCM2 (Flannigan *et al*. 2005).

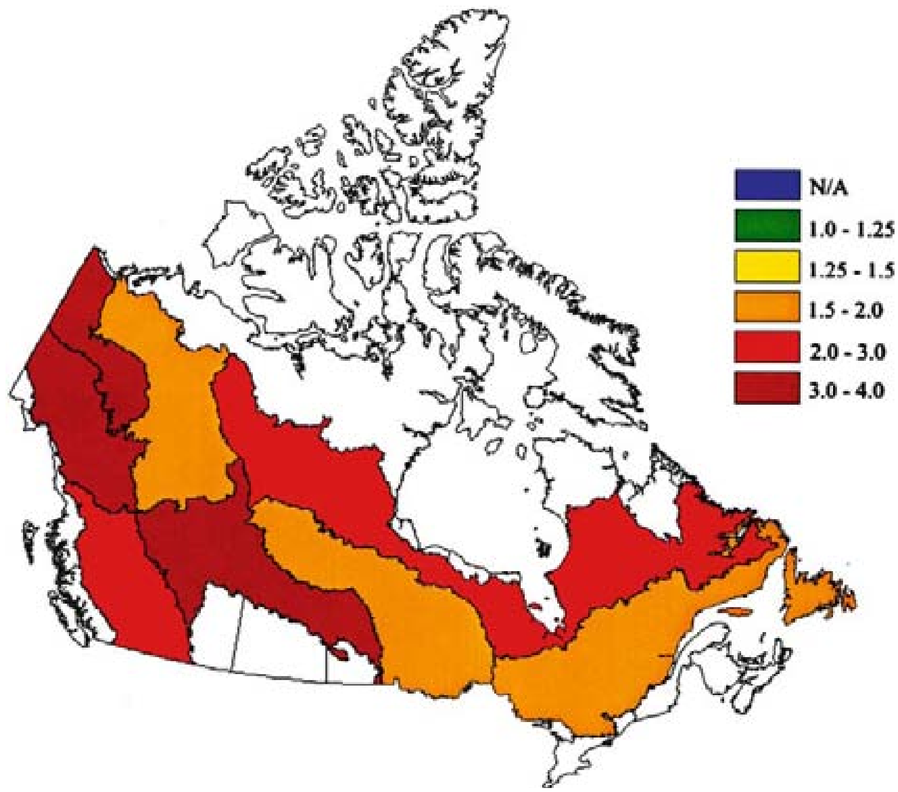


Figure 42. Increases in area burned by ecozone based on projections from HADCM2 (Flannigan *et al*. 2005).

Results from CGCM2 show a smaller increase in area burned for most ecozones, although none show a decrease. Area burned for Saskatchewan ranges from a 1.0 to 1.25 times increase for the Boreal Plain Ecozone to a 1.5 to 2.0 times increase for the Boreal Shield Ecozone. Results from HADCM2 show a greater increase, with area burned increases of 3.0 to 4.0 times in the Boreal Plain and 1.5 to 2.0 times for the Boreal Shield. Flannigan *et al*. (2005) point out that this analysis was done at a very coarse spatial scale and that it does not include such factors as changes in vegetation, ignitions, fire season length, and human activity (fire management and land use activities) that may influence area burned.

Balshi *et al*. (2009) used a statistical procedure to relate current fire weather index values to current area burned and then used that relationship to project future area burned using output from CGCM2 with the A2 and B2 SRES scenarios. This analysis was used to predict annual area burned through the year 2100 across Alaska and western Canada. Relative to 1991–2000, the results suggest that average area burned per decade will double by 2041–2050 and will increase on the order of 3.5–5.5 times by the last decade of the 21st century. Figure 43 shows estimated area burned for western Canada by decade for both scenarios.

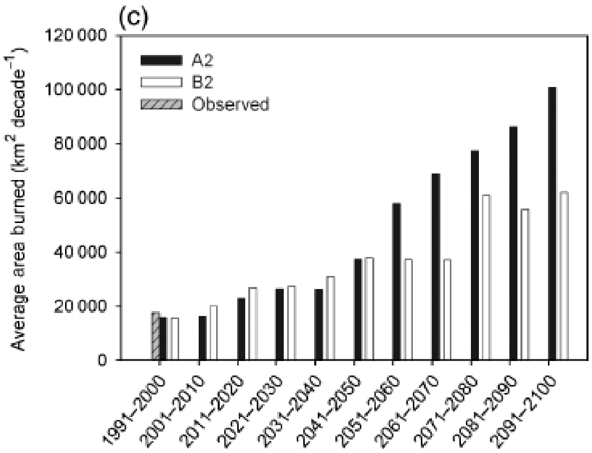


Figure 43. Area burned in western Canada for the A2 and B2 SRES scenarios. Also included is the observed area burned for the period 1991-2000 (Balshi *et al*. 2009)

Area burned increases dramatically after 2050, especially for the A2 scenario. These authors also point out that other variables such as lightning strikes, fire suppression, and the successional dynamics following fire may help to more accurately predict area burned on an annual basis. Their results are remarkably similar to those of Flannigan *et al*. (2005) even though the analytical approach was different.

Insect outbreaks

In general, warmer and dryer conditions will tend to support increased outbreaks of forest pests. Volney and Hirsch (2005, p. 664) suggest that

> "For all [insect] species, outbreaks persist longer at the southern margins of western boreal forests. It is thus attractive to speculate that these insects collectively could be instrumental in driving vegetation changes at the southern boreal forest margin in a warming climate…. The general consensus is, however, that the incidence and area affected by defoliators will increase as the climate gets warmer and drier."

Spruce budworm is an important insect pest in Saskatchewan and has been the subject of a spray control program for many years (R. McIntosh, Saskatchewan Environment, personal communication). Budworm is likely to be encouraged by climate change in Saskatchewan, although exactly how this will evolve is a complex question (Volney and Fleming 2000). The authors conclude that the occurrence of outbreaks at a higher frequency toward the warmer margins of the host range is often associated with drought. It is thus quite reasonable to conclude that the insects may be partly responsible for the decline and ultimate extirpation of these stands at the southern margins of the hosts range. In contrast, late spring frosts have a role in terminating outbreaks in the northern reaches of the host range and may be responsible for limiting outbreak areas at these colder extremes. Accordingly, insect outbreaks may move north in Saskatchewan as temperatures warm, and will likely have major impacts at the southern limit of the host trees' range given the increased likelihood of droughts (Hogg and Bernier 2005).

Mountain Pine Beetle (MPB) is another species with the potential to become an important pest in Saskatchewan. The MPB is currently in a major outbreak phase in the BC interior. The beetle is limited by the occurrence −40 °C temperatures in early winter, restricting its main extent to approximately the BC-AB border. In 2006 a large wind event transported a large population of beetles into Alberta, so that their current distribution extends to the Slave Lake region of central Alberta. With warming, this limiting temperature is likely to occur further to the north and west, allowing the beetle to spread into jack pine in the Prairie Provinces. The MPB has been shown experimentally to develop successful populations in jack pine, so there is every expectation that jack pine will prove to be a suitable host (Langor *et al*. 2006). The overlap in range and hybridization between jack pine and lodgepole pine in north-central Alberta will provide the physical connection between the two host species. The long-term effect of insect outbreaks on forest management is difficult to predict, but recent research suggests increased tree mortality resulting from the interaction of insects, drought and fire in the southern margin of the boreal forest in the Prairie Provinces (Hogg and Bernier 2005, Volney and Hirsch 2005).

Finally, insects moving into Saskatchewan from southern locations is also expected as temperatures warm. No evidence of this has been seen so far, but experience with other invasive species (*e.g.* emerald ash borer in Ontario) has shown that some insects can quickly adapt to new locations and will likely thrive as described above.

Forest productivity

Forest productivity (*i.e.* tree growth) is the net result of a wide variety of environmental factors, especially water and nutrient availability. In addition, the increased atmospheric carbon dioxide associated with future climate will affect growth. Carbon dioxide affects tree growth in two ways. First, it enhances growth directly because the diffusion of CO_2 into the leaves is more efficient at higher atmospheric concentrations (called the CO_2 fertilization effect) (Long *et al*. 2004). A survey of literature on CO_2 fertilization found that tree biomass increased an average of 23% in a doubled CO_2 atmosphere as compared to current CO_2 levels (Norby *et al*. 2005). In addition, CO_2 results in greater water use efficiency, since water loss through transpiration is reduced per unit of carbon uptake (Long *et al*. 2004). However, these results are based on artificial laboratory or manipulated field studies, and may not represent the actually response of trees in the "real world". In general, forest growth may either increase or decrease under future climate conditions, since the potential effects of CO_2 may be reduced due to limitations in other environmental resources (nutrients, water) or enhanced when other resources are not limiting (Oren *et al*. 2001). Johnston and Williamson (2005) used a forest ecosystem model to explore responses of white spruce productivity under a range of future climate conditions in Saskatchewan. They found that even under severe drought conditions, increased water use efficiency due to increased CO_2 concentrations resulted in an increase in productivity relative to current conditions. However, productivity declined by about 20% when this effect was not included in the model.

The factors described above will interact in forest ecosystems in ways that are very difficult to predict. Johnston *et al*. (2008a) undertook an integrated analysis of potential climate change impacts on the “Island Forests” in central Saskatchewan. These are patches of isolated forest cover, typically surrounded by agricultural land. They occur on sand dune deposits that are somewhat higher in elevation that the surrounding land. Figure 44 shows the location of these areas in Saskatchewan.

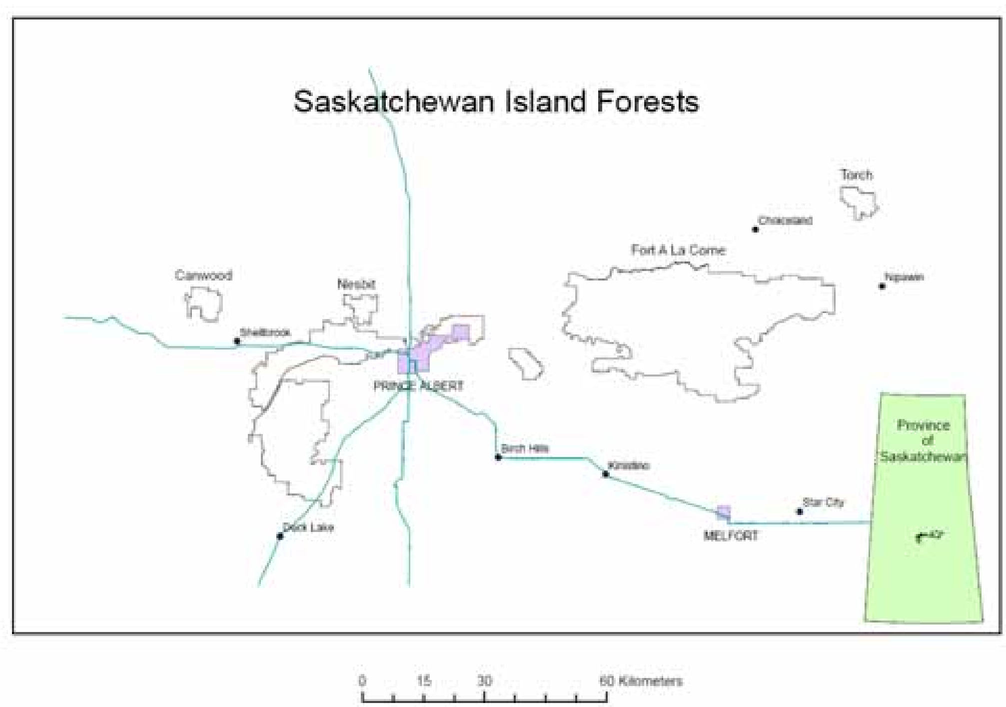


Figure 44. Location of the Island Forests in central Saskatchewan.

The following is extracted from a report entitled "The Impacts of Climate Change the Island Forests of Saskatchewan". For further detail see Johnston *et al*. (2008a).

The Island Forests represent the southernmost extreme of the boreal forest in central Saskatchewan. These isolated patches of forest occur on sandy deposits formed near the end of the last glacial period, which because of low agricultural suitability have remained forested while the surrounding lands have been cleared and farmed. Most of the stands in the island forests are dominated by either jack pine (*Pinus banksiana*) or trembling aspen (*Populus tremuloides*).

The transition from forest to grassland in this region is linked to climatic moisture balance, and the island forests are close to the threshold at which moisture becomes insufficient to support continuous forest vegetation. Hogg (1994) mapped a climate moisture index (CMI) for the Prairie Provinces, calculated as annual precipitation minus annual potential evapotranspiration. The zero value of this index coincides almost exactly with the southern boundary of the boreal forest across Alberta, Saskatchewan and Manitoba, indicating that positive values coincide with forest while negative values coincide with grassland/aspen parkland vegetation. Maps of average CMI presented by Hogg *et al*. (2007) showed that The Fort à la Corne Forest is roughly at a CMI of -5 cm, and the Nisbet Forest at -10 cm (Hogg 1994). This indicates that the island forests are climatically marginal for boreal forest, with the Nisbet Forest slightly drier than the Fort à la Corne Forest. The predominantly sandy soils in these forests allow rapid infiltration of rainwater, favoring deeper-rooted trees over shallow-rooted grasses, and allowing forest to develop in this forest-marginal climate.

The Island Forests may already be showing signs of climate change impacts, and are likely to be severely affected in the future. The number of days with minimum temperatures less than -40°C have declined in the past three decades, and are expected to decline further with a warming future climate. It is this temperature threshold that limits the reproduction of mountain pine beetle and the parasitic plant dwarf mistletoe, both pests of jack pine. An additional factor leading to the forest's high vulnerability is its age. Nearly 60% of the forest is more than 70 years old, with an additional 24% between 50 and 70 years old. These age classes are the most susceptible to pests such as the mistletoe and mountain pine beetle. As indicated above, the Island Forests are largely on sandy soils with poor water-holding capacity. The future climate is expected to be drier than at present, making this area highly susceptible to droughts. This will add to the likelihood of forest decline due to pests, as well as to declining tree growth. Modeling analysis for the Island Forests has indicated that future moisture availability may become similar to that currently in southern Saskatchewan (*e.g.* Swift Current), and that tree growth could decline by up to 30% (Johnston *et al*. 2008a).

For these reasons, the Island Forests are an excellent example of the "canary in the mine shaft", where the impacts of climate change are likely to occur earlier than in the contiguous boreal forest to the north. This area could form part of a national "early warning" network of intensively monitored sites in which the signs of climate change will emerge first. It is also important to link sites in the Island Forests to existing monitoring programs such as the CIPHA study (Climate Impacts on the Productivity and Health of Aspen) being conducted by the Canadian Forest Service's Northern Forestry Centre in Edmonton (Hogg *et al*. 2005). While the CIPHA study is currently focused on aspen, additional sites could be added and the network expanded to monitor forest health and productivity in other forest types such as jack pine in the Island Forests. Another opportunity is to link climate change monitoring to existing provincial forest monitoring programs. These usually comprise networks of permanent plots to monitor the effects of forest management activities on forest ecosystems. Existing programs in the Prairie Provinces could provide important early information on climate change impacts in these vulnerable areas.

Several current and planned developments will affect the Island Forests and will interact with the effects of climate change. Demand for recreation activities from growing urban populations, exploration and likely extraction of diamonds, other mining potential and continued forest harvesting will all have impacts on the Island Forest ecosystems. This area is important to the local forest industry, particularly to the First Nations involved in the First Nations Island Forests Management Inc. An integrated land management approach in which all resource development actors cooperate on minimizing their footprint is essential for managing the impacts of development in this area, particularly in light of some of the ecological vulnerabilities identified above.

Dealing directly with the vulnerabilities described above may also be possible. For example, dwarf mistletoe, older forest age classes and the potential for a MPB outbreak all add to the high fire hazard in the Island Forests. An approach to reducing fire hazard has been developed by the Canadian Forest Service and has shown success in several provinces, including Saskatchewan. This approach, known as FireSmart (Hirsch *et al*. 2001), involves activities at both the local stand level and the landscape level. At the local level, the focus is on communities in fire-prone forest environments. Surveys are conducted in the community that indicate sources of risk, *e.g.* tree canopies near houses, flammable roofing material, openings for embers beneath porches or decks, etc. These risk factors are quantified and suggestions made for reducing them. This program has been applied to several forest communities in Saskatchewan (*e.g.* Waskesiu, Candle Lake, etc.) and widely applied in Alberta. The benefits include both a reduced fire risk and an educated public that can assist others in reducing risk.

The component of FireSmart applied at the landscape level involves treating forest stands to reduce flammability and lower fire behavior. Examples include replacing coniferous stands with deciduous stands through timber harvesting in order to break up highly flammable contiguous stands; harvesting diseased and insect-killed trees; and targeting harvest operations at the most vulnerable older stands to increase diversity of age-classes. These activities may incur extra expense and will take several decades to have an impact, but the time to start considering these ideas is now before the risks increase. An additional advantage is that by reducing fire hazard at the landscape level, the risks for other impacts (insects, disease) are also reduced. Forest harvesting in the Island Forests could be scheduled to reduce the insect, disease and fire hazard as much as possible while still providing forest products.

Forest management also can potentially deal with some of these vulnerabilities. Immediate and aggressive regeneration of harvested (and possibly burned) stands will help ensure that forest cover is maintained. Selection of seed from drought-resistant individuals could also assist with maintaining future forest cover. Experimental planting and monitoring of exotic species (*e.g.* red pine, ponderosa pine) may help identify species that will grow better under future conditions.

Recent studies by Carr *et al*. (2004) and Thorpe *et al*. (2006) explore these alternatives in more detail.

In spite of these opportunities for reducing risk, the Island Forests may permanently lose forest cover in the future. Regeneration failure following fire or harvest is likely on some sites. This suggests that management planning needs to include the potential for change to grasslands in some locations so that this can be accommodated with a minimum of disruption to the sustainable use of these landscapes.

Changes in species distributions

As climate changes, tree species will begin to respond in ways that will eventually result in their establishment in new locations. In particular, the southern edge of the boreal forest in Saskatchewan is particularly vulnerable to changes in, or loss of, forest cover. As described above, this area is at the southern limit of moisture availability for tree growth, and even a slight decrease in available soil moisture will likely mean loss of forest cover on drought-prone sites. In particular, the environment immediately following a disturbance event will be critical in determining successful species re-establishment. For example, Godwin and Thorpe (2009) reviewed the success of natural tree regeneration following a 1989 fire near Prince Albert. They found that regeneration was limited in many parts of the burned area, and concluded that higher than average temperature and lower than average soil moisture were probably responsible. These conditions are projected to become more frequent under future climate (Hogg and Bernier 2005, Lemmen *et al*. 2008), so regeneration failure, especially in the southern boreal forest is increasingly likely.

McKenney *et al*. (2007) determined the climatic tolerances (the "climate envelope") for 130 North American tree species and mapped the re-distribution of these species under future climate scenarios. They found that, under a scenario [the scenario refers to the ability to disperse, not a climate scenario] in which species were able to fully occupy their future climatic niche, species' ranges decreased in area by an average of 12% and shifted northward an average of 700 km. Under a scenario in which dispersal into new areas was extremely limited, species' ranges decreased by 58% and shifted northward an average of 330 km. Due to large-scale land use change and the built environment in the southern and central Saskatchewan, species' ability to disperse to new habitats may be extremely limited in some areas and natural migration unable to keep pace with the shifting climate.

In general, research has shown that species will migrate northward, at rates determined by their dispersal abilities and the suitability of habitat (McKenney *et al*. 2007). However, this general large scale trend will be affected by the small-scale pattern of landscapes and availability of resources. For example, trees will likely be lost from the southern margin of the boreal forest due to lack of available moisture but will preferentially survive in more northerly locations where rainfall is higher. However, the small-scale pattern of topography will likely result in moisture being sufficient for tree growth in some southerly locations. Therefore, species may persist in some isolated locations, resulting in a fragmented mosaic of forest and grassland rather than a wholesale movement of all tree species to the north.

Operational impacts

In addition to ecosystem effects described above, climate change will also likely bring change to the physical environment that will affect forest operations. Climate models suggest that winters will warm more than other seasons and that precipitation will increase, with a greater proportion falling as rain (Barrow 2009, Lemmen *et al*. 2008). A major implication for forest operations is the impact on the winter harvest season. In many boreal landscapes, conditions are too wet during the summer to operate, so harvesting and hauling are done in the winter when soils are frozen. As part of work done for the Mistik Management 20-year Forest Management Plan, data from the Canadian Regional Climate Model was used to determine the changes in liquid soil water content under future conditions (Johnston 2007) . Results are shown in Figure 45. Increases in liquid soil water are particularly apparent in spring (March and April) and in early winter (November and December). Discussions with Mistik personnel indicated that the increase in liquid soil water (*i.e.* reduction in frozen soil) would be particularly problematic in the November-December period when much of their harvest activity takes place. In addition, warmer and wetter springs will likely restrict the period of spring hauling, thereby increasing costs and affecting timely delivery to the mill site (A. Balisky, Mistik Management, personal communication). Other impacts include shallower snow depths affecting the ability to store seedlings in the field for spring planting.

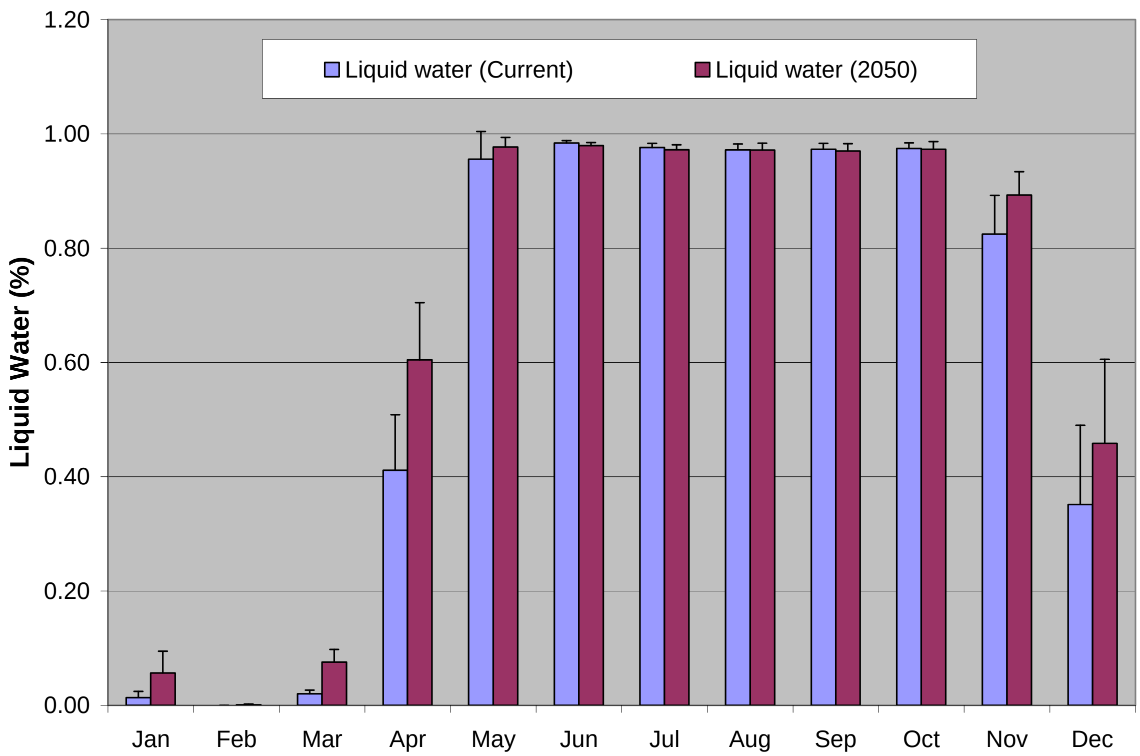


Figure 45. Change in liquid water (versus frozen water) between 1980s and 2050s based on Canadian Regional Climate Model output. Error bars represent one standard deviation.

Warmer winters and springs with more precipitation occurring as rain will also affect companies' ability to haul trees to the mill in spring, with more frequent road closures and impacts to infrastructure (*e.g.* culverts, bridges, stream crossings).

Summary of adaptive capacity in the forest sector

Johnston *et al*. (2008b) carried out an analysis of the adaptive capacity of the forest sector in the Boreal Plains Ecozone. Their general conclusions included the following:

Need for greater local authority and autonomy in decision making

Climate change effects will vary from place to place. There may, therefore, be a need for local adaptation and for transfers of authorities and autonomy in a way that allows individuals, firms, towns, and resource managers to more effectively adapt to local changes. The actual trend, however, may actually be in the opposite direction, with increased consolidation and centralization in the forest industry (FPAC 2005). A trend toward more centralized institutions may limit the amount of autonomy, control, flexibility, and power that decision makers have relative to implementing adaptation responses that are tailored to local requirements.

Knowledge gaps about future impacts

There are significant knowledge gaps about climate change impacts on communities at locally relevant scales. Knowledge gaps prevent local decision makers from taking action and/or result in the wrong choices. The interviews conducted in the course of the study suggest that decision makers generally have insufficient information about future climate change effects upon which to plan for climate change effects or base adaptation decisions. The various communities indicated that they are concerned about climate change but at the same time, they have not developed plans or strategies to deal with or prepare for climate change. One of the stated reasons was a lack of information about climate change and climate change impacts at locally relevant scales. Thus, more and better organized science to deal with knowledge gaps that are impairing adaptation policy and decision making is needed. However, the multifaceted nature of climate change requires a trans-disciplinary approach to climate change impacts and adaptation science, in which stakeholders and scientists jointly determine the direction of the scientific investigations that are required.

Rigid institutions

Our interviews indicated overwhelmingly that institutional factors are most limiting to adaptive capacity – particularly with forest management. Institutional barriers impairing climate change adaptation in the forest management community are significant. An important factor is a lack of high level executive support for preparing for climate change by taking into account rules, regulations, norms, standards, planning systems, and property rights configurations. This is seen as essential before any kind of institutional change can take place. It is not evident as of yet in the boreal plains ecozones.

In the case of forest management, policies and practices have not been modified to account for climate change. New concepts such as adaptive management and risk management are not being implemented. Forest management continues to be prescriptive and is generally based on the assumption that the future will be like the past. Forest management plans generally do not take climate change into account. Similarly, aboriginal and non-aboriginal communities are not planning for climate change.

Institutional barriers to adaptation among provincial regulators are related to forest policy that usually assumes a forest that remains substantially the same over time. A similar perspective probably applies to institutions and policies affecting resource-based towns and First Nations communities. Policy is generally based on what has worked in the past rather than anticipating what is likely to happen in the future. This is particularly a problem with climate change given the uncertainty about future conditions. A high level of uncertainty makes acceptance of innovative ideas difficult, especially if the proposed alternative lies far outside of accepted practice. At the same time, a do-nothing approach has the potential for increasing future impacts on communities in the boreal plains ecozones. In the case of forest management, long-term agreements that are stipulated by government may reduce the adaptive capacity of both industry and provincial regulators by "locking-in" levels of harvest or other aspects of forest management and may prevent adaptation options from being implemented. Innovative forest management practices that have both immediate and long-term benefits may become more difficult to apply given relatively inflexible tenure agreements. Similarly, agreements that continue to link industrial wood-processing facilities and management of large forest landscapes may reduce adaptive capacity in that the company must maintain a range of mill and forest management specialists, rather than focusing on one aspect or the other. A tenure agreement that is specific to the forest landscape, (*i.e.*, one that severs the appurtenance requirement inherent in some large scale forest management agreements) will likely result in agreements with companies that specialize in forest management. The province of BC, for example, has eliminated the linkage between mill processing requirements and timber supply as part of an exercise to modernize its forest policy regime.

Need for enhanced science capacity at all scales and across contexts

Climate change is a complex science-based issue. Assessment of impacts and developing adaptation demands the best available science of impacts and adaptation, an expanded knowledge base, and reduced uncertainties. At the same time the science will need to be operationalized and used to support policy and decision making. However, forest managers will need to have the capacity to interpret and apply impacts and adaptation science on the ground and in the context of policy development. Recent experience has shown that close interaction among scientists and practitioners (*i.e.* "embedded science") within firms and with management agencies increases adaptive capacity.

Forest companies and management agencies vary widely in their technical expertise, with a few employing several Ph.D.-level scientists while others have very little advanced scientific capacity. Generally science capacity at the firm level among most forest companies in the boreal plains is low. Similarly the ability to assess impacts and develop science based adaptation responses in resource based communities is relatively low. Discussions with industry, government managers, and leaders in resource based towns indicated that there is a relatively low level of climate science capacity and few mechanisms through which managers and community leaders could access climate science in ways that are useful to them.

Climate change should be included in long term planning

All forest management jurisdictions in Canada require some type of long-term forest management plan, typically on a 20-year time horizon (although the planning horizon for timber supply analysis can be up to 200 years). Experience in other projects and discussions with industry managers indicate that the forest management planning function provides an excellent vehicle for considering climate change effects and adaptations. The relatively long time horizon and the generally strategic focus of the plans means that climate change considerations can be brought in at a temporal and spatial scale consistent with the current state of understanding of climate change impacts, and consistent with the scale of forest management decision-making. In addition, the plans are required under most provincial legislation, so this is an activity that the companies will be undertaking regardless and is not a separate activity that would add additional cost to their operations. We advocate the development of planning guidelines that could be used across all jurisdictions in order to provide guidance on how impacts and adaptation considerations could be integrated into forest management plans. These would necessarily be general in order to accommodate variability among jurisdictions and biophysical conditions, but could be developed in a way that would be helpful to both industry and government planners. Similarly, incorporating climate change into community strategic and economic development plans would enhance the capacity of these communities to adapt.

Assessment of management-level and policy-level adaptation options and barriers

Management-level adaptation

An important principle is that the forest manager must be the primary author of adaptation options. The role of scientists and other experts and stakeholders is to support development of local options rather than imposing them "top down", *i.e.* adaptation occurs at the local level but is empowered by other levels of government and institutions. "Embedded science" has been shown to work well (Van Damme *et al*. 2008). In this approach, scientists work closely with forest managers in identifying the research questions and bringing their scientific expertise (*e.g.* climate change science) to the forest management planning exercise.

Spittlehouse and Stewart (2003) and Spittlehouse (2005) suggest some adaptation options for forest management. These include:

- Gene Management: Breeding for pest resistance and climate stresses and extremes
- Forest Protection: Altering forest structure and developing "fire-smart" landscapes, *i.e.* creating areas of reduced flammability through fuel modification

- Forest Regeneration: Assisting the migration of commercial tree species from their present to future ranges through artificial regeneration; possible introduction of exotic species

- Silvicultural Management: Pre-commercially thinning to enhance growth and insect/disease resistance and limit water use in drought-prone areas

- Forest Operations: Mitigating climate change impacts on infrastructure, fish, and potable water supplies stemming from changes in the timing of peak flow and volume in streams resulting from increased winter precipitation and earlier snow melt

- Non-timber Resources: Minimizing fragmentation of habitat and maintaining connectivity

- Park and Wilderness Area Management: Manage these areas to delay, ameliorate, and direct change

- Societies' expectations: New products and new uses for the forest; loss of previous uses; changes in forest recreation values

- Forest products: New products from both old and new tree species; increased value of non-timber forest products; increased use of fire and insect-salvage timber for bioproducts/bioenergy

- Monitoring: increased need for careful monitoring of forests for signs of climate change; focus on forests near the margins of their traditional ranges

Barriers to implanting these options include lack of species-specific data on suitable genetic stock for new climates; regulations that prevent movement of seed to new areas based on projected climatic change; policy that may prevent the introduction of new (exotic) species if these are found to be the best adaptation option; lack of economic value preventing pre-commercial thinning or other silvicultural actions; and cost of implementing new infrastructure to deal with increased spring flows in stream channels.

Policy-level adaptation

Policy-level adaptation needs to focus on increased flexibility, increasing the ability of policy-makers to deal effectively with surprise and novelty, and improving the ability of forest managers to make decisions based on local conditions. The forest tenure system may prevent this flexibility and should be carefully evaluated as to its ability to deal effectively with changing circumstances (Haley and Nelson 2007). Saskatchewan's Forest Management Act is relatively new and many have suggested that it incorporates flexibility and can change when required. However, a rigorous review of the Act and other policy related to forest management should be carried out specifically with regard to its ability to help policy-makers cope effectively with climate change. Other provincial policy that may have effects on future forest management (*e.g.*

biodiversity policy) should also be evaluated as to its support for adaptation in the forest sector (Johnston *et al*. 2008b).

Climate change will not occur in isolation. Many other sources of change are also affecting the forest sector, many of which are more important in the short term than climate change. Some of these agents of change directly affect the adaptive capacity of the forest sector. Globalization, and its effects on the Canadian forest industry, has resulted in an economic downturn in the industry and record low levels of investment. This in turn affects the companies' ability to be innovative in developing new products and in undertaking innovative forest management practices. Both will be required for adapting to the new forests that will emerge as the climate changes. Similarly, demographic change in rural communities, increasing aboriginal populations and changing societal expectations of forest benefits will affect the forest sector's ability to adapt appropriately to climate change (Johnston *et al*. 2008b).

Scenarios of future social and economic conditions could be linked to climate and biophysical impact scenarios to enable a comprehensive analysis of Saskatchewan's future. Recent regional climate change assessments in the UK (Holman *et al*. 2005a,b) and the European Union (Schroter *et al*. 2005) have shown that social-economic scenarios are often more important than climate scenarios in vulnerability assessments, particularly in determining economic impacts and adaptive capacity. The approach these authors have taken is to "downscale" the scenarios developed in the Special Report on Emission Scenarios (SRES, Nakicenovic and Swart 2000). For example Abildtrup *et al*. (2006) described the development of agricultural scenarios used in the ATEAM assessment (Schroter *et al*. 2005). There is a critical need to develop these scenarios for Canada, ideally at the regional or provincial level.

Conclusions

Saskatchewan's forests are already vulnerable to a range of natural disturbance and climate-related factors. Fires, insects and drought have had major impacts on the forest and will continue to do so regardless of climate change. Warmer, drier conditions in the future will likely make these impacts stronger, and the interaction of these factors will likely magnify the impacts even further. In particular, the southern margin of the boreal forest will become increasingly vulnerable to a range of climate change impacts and may eventually loose forest cover all together. On the positive side, there may be some locations where other conditions are not limiting and CO_2 fertilization may result in increased productivity.

It must be kept in mind, however, that the impacts of climate change on forest ecosystems are very difficult to predict. Ecosystems are extremely complex with many interacting processes that vary over time and space. In addition, our ability to forecast climate change and how it will affect ecosystem processes requires more research on these complex issues to better understand the future vulnerabilities of Saskatchewan's forests.

The adaptive capacity of the forest management community in Saskatchewan is high in terms of the ability to implement sustainable forest management. However, the science capacity regarding the details of climate change impacts is not high, and increasing the interactions between scientists and managers should be a priority. The concept of "embedded science" has shown to be effective in educating both managers and scientist as to how adaptation should be implemented. In addition, further research in which information on impacts is provided at a scale consistent with decision-making is essential for climate change to be considered in management.

Forest management institutions need to be examined for the extent to which they support or hinder the development and implementation of adaptation options. Consideration of new species, assisted migration of existing species and populations, and revised tenure agreements are examples of policy changes that could assist in more effective adaptation. Local autonomy and flexibility in decision-making will become increasingly important in an environment in which conditions are changing rapidly and where the past is no longer a guide to the future.

SYNTHESIS

Key Findings

This report provides an overview of the scientific understanding of the impacts of climate change on Saskatchewan's water resources soil landscapes and ecosystems, and the key sectors of the provincial economy, agriculture and forestry, that depend directly on this natural capital. This overview of impacts was based on a review of scientific literature, expert interpretation, and new information on climate changes that are projected for Saskatchewan. The other major component of this biophysical assessment of climate change in Saskatchewan is the identification and discussion of adaptation options and strategies that could limit exposure to future climate risks and provide new opportunities from more favourable conditions The general approach is a vulnerability assessment framework of exposure to climate risk, sensitivity to climate change and variability, and an assessment of adaptive capacity, the potential for responses to lower risk and take advantage of new opportunities. This concluding section provides a summary of key findings that emerge from synthesis of the content of this report and a brief overview of options for managing the impacts of climate change through adjustments in policy, management practices and decision-making processes.

Saskatchewan is warming at a faster rate than the global average and our future climate will be outside the range of natural variability.

Recent trends in annual and seasonal temperature strongly suggest that Saskatchewan is not getting hotter, but rather 'less cold'. There has been a greater increase in daily minimum (as opposed to maximum) temperatures and the largest warming has occurred during winter and early spring, resulting in a longer frost-free period and more growing degree days. Historical trends in the summer climate moisture index (CMI = precipitation – potential evapotranspiration) suggest a significant decreasing trends of between 1 and 4 mm/yr in southern Saskatchewan. The climate experienced in Saskatchewan over the past half century, while variable, did not encompass the range of conditions captured by records of the past millennium and projected for the near future under global warming.

Across a range of global climate models and greenhouse gas emission scenarios, there is a consistent increase in mean annual temperature throughout Saskatchewan. Most climate change scenarios also indicate an increase in annual precipitation. These are more favourable climatic conditions for most activities, and especially agriculture; however most of the extra heat and water that has been observed and projected occurs in winter and spring. A scenario of less summer precipitation, falling in fewer and more intense storms, would result in drier, possibly much drier, conditions in the mid to later stages of the longer warmer summers. While this shift in average conditions to warmer wetter winters and drier summers is almost certain, most of the risk from climate change will be from an increase in the range of extremes, including year-to-year variability, and the climate scenarios that project drought, and unusually wet years, with greater severity and frequency than in the past.

The major impacts are shifts in the distribution of natural resources

The major biophysical impacts of climate change in Saskatchewan are seasonal, annual and geographic shifts in the distribution of water resources and plant and animal species. In some cases annual streamflow could increase for certain scenarios and under moderate degrees of climate change. The median scenario for the South Saskatchewan River is an 8.5% decrease in mean annual flow for the 2050s. Small scale hydrological models for prairie streams suggest a 24% increase in spring runoff by 2050 followed by a 37% decrease by 2080 as the winter snow cover becomes discontinuous. Initially there may be increases in prairie runoff but as climate change progresses later in the 21st C there may be dramatic drops in runoff and the flow of small streams to wetlands and depressions and to small prairie rivers. These trends in mean annual runoff are very likely but perhaps the more challenging issue is the shift of water balance towards earlier runoff, leaving less surface water for mid to late summer in average years and much less during the droughts that are expected with increased severity.

The projected climate changes will alter environmental conditions to the benefit of some species, in some cases invasive, and detriment of others, often with economic consequences. New landscape ecosystems might evolve; for example, a drier climate in southern Saskatchewan could potentially support shortgrass prairie currently found farther south. Change in terrestrial ecosystems will be most visible at ecological gradients: isolated forests (*e.g.* Cypress Hills), and the fringes of the boreal forests. Aquatic habitats will be stressed by the lesser amounts of surface water and the associated changes in water quality. Changing ecosystems could make the habitats of disease carrying vectors more hospitable. The increased stress on aquatic ecosystems from warmer and drier conditions, and loss of wetlands, could place prairie aquatic species at risk of extirpation and cause declines in migratory waterfowl populations.

One of the most certain projections is that extra water will be available in winter and spring and summers generally will be drier as the result of earlier spring runoff, and a longer warmer summer season of water loss by evapotranspiration. Increased aridity and water scarcity most likely will be realized by more frequent drought of longer duration and greater severity. Sustained drought has cumulative impacts and prevents the recovery of natural and social systems during intervening years with normal to above-average water supplies. They also are more likely to exceed soil moisture thresholds beyond which landscapes are more vulnerable to disturbance by wind erosion and from less frequent but more intense rainfall; and soil moisture thresholds below which landscapes are more vulnerable to disturbance and desertification.

The consequences of a shorter, warmer winter

Much of the observed and projected warming in Saskatchewan is during winter and spring, such that the frost-free growing season is getting longer and expected to get significantly longer as the climate warms. We also, however, will lose the advantages of a cold winter: transportation in northern Saskatchewan over frozen ground, lakes and rivers; fewer pests and diseases, and snow, the most abundant, reliable and predictable source of water. Snowmelt is the primary hydrological event of the year for the major rivers that derive from the Rocky Mountains and for the small streams and rivers that arise in Saskatchewan. Climate change impacts on water resources are therefore focused on changes to snow accumulation, snowmelt and infiltration to frozen soils.

Increased farm and forest productivity during a longer warmer growing season will be constrained by other climate impacts

A longer warmer growing season will favour diversification of prairie agriculture and higher crop, pasture and forest productivity. Greater heat (growing degree days) and concentrations of CO_2, and higher water use efficiency, will favour increased forest, grassland and crop productivity. However, higher productivity will be limited by available soil moisture. Future climate change impacts on crop production are still uncertain, but consistent with recent changes and tending to converge towards increasing trends in the near-term until certain thresholds of climate change are reached. This upward trend is then followed by average decreases and interrupted by large losses accompanying severe climatic events, such as droughts and excessive moisture. The complex interactions of the effects of insects, diseases, and weeds on agricultural production are still not understood well enough to offer substantial findings for projected impacts. Although warming winters are generally favorable for livestock production and management, increasing threats of stresses related to heat, water, insects and diseases, and other climate hazards tend to offset gains. Extreme weather and climate are “wild cards”. A trend of increasing frequency and severity of extreme events is fairly certain, but the detrimental effects are not considered well or at all in future estimates of agricultural production.
A potential increase in plant productivity with a longer and warmer growing season and increasing atmospheric CO_2 may be limited or overwhelmed at many sites by moisture limitations or other constraints. Fires, insects and drought have had major impacts on Saskatchewan’s forests and will continue to do so. Warmer, drier conditions in the future, and interaction of factors, will likely magnify the impacts. In particular, the southern margin of the boreal forest will become increasingly vulnerable to a range of climate change impacts and may eventually lose forest cover all together. On the positive side, there may be some locations where other conditions are not limiting and CO_2 fertilization may result in increased productivity.

Climate change impacts tend to be adverse

The impacts of climate change tends to be adverse because our communities and resource economies are sensitive to fluctuations in the quantity and quality of natural capital and they are not adapted to the larger range of climate conditions projected under global warming. From the short perspective of Saskatchewan’s post-settlement history, climate and water seem rather consistent and thus resource management practices and policies reflect perceptions of relatively abundant and consistent water supplies and ecological services. Future water and ecosystem management will have to abandon the assumption of a stationary environment, as climate change produces shifts in climate variability, biodiversity, disturbance regimes, and distribution of water resources and ecological services.

The net impacts will depend on degrees of climate change and adaptation

The net impacts of climate change are not clear because they depend heavily on assumptions about rates of climate change, coping ranges and the effectiveness of adaptation measures. South of the Churchill River, nearly all of Saskatchewan's ecosystems and water resources are managed. Most impact assessment has assumed no adaptation or made simple assumptions. This reflects a lack of understanding of adaptation processes and the difficulty of predicting changes in public policy and socio-economic factors. There is a gap in our understanding of the extent to which existing management practices and public policies either encourage or discourage the implementation of adaptive strategies. There is also a need for determining the relative importance of adaptive responses versus other priorities, and to develop approaches that incorporate climate change considerations into existing policy instruments. Planned adaptation is a component of adaptive resource management and sustainable economic development.

The major threats are understood with the least certainty

The recurring impacts of drought in Saskatchewan suggest that the severity and duration of future droughts will determine much of the impact of climate change. Droughts, and flooding to a lesser extent, could limit opportunities provided by a warmer climate and will challenge our capacity to adapt to changing conditions. Unfortunately climate models simulate extreme events and the variability of hydroclimate with much less certainty than trends and variability in temperature variables. Nearly all climate assessments are based on climate change scenarios derived from GCMs. These scenarios give shifts in mean conditions between decades. The climate will actually change by fluctuating, from season to season and year to year, above and below these trends. Estimates of variability and changes in extreme values are available on a global scale, but there are few projections at the regional scale suitable for provincial vulnerability assessment.

A key finding of this biophysical impact assessment therefore is that the gap in our knowledge of climate variability versus climate change is problematic for evaluating impacts and developing appropriate adaptation strategies. While the two scales of climate variation are linked, water resources and ecosystems respond in the short-term to departures from normal precipitation and temperature rather than to trends or shifts in climate variables. The length and timing of wet and dry cycles strongly influence the management of land and water resources. Drought is the most costly climate hazard and thus scenarios of future climate should target estimates of frequency, severity and duration of departures from average moisture conditions.

Future options for impacts and adaptation management

Advancing climate change research

The scientific support for adaption for climate change is clearly documented in this report, the companion report "Climate Scenarios for Saskatchewan" (Barrow 2009) and recent regional (Sauchyn and Kulshreshtha 2008), national (Lemmen *et al*. 2008) and global (IPCC 2007) assessments of climate change impacts and adaption. The information exists to support adaptive responses to prevent or minimize impacts, although significant knowledge gaps remain for many variables, sectors and impacts. Therefore, a major and important adaptation strategy is further study of climate change to address important knowledge gaps.

Options for further research to improve the reliability and utility of climate change scenarios include:

1. Expanding the set of derived climate variables, such as mean frost-free period, mean growing season precipitation and summer moisture index.
2. Expanding the number of scenarios considered and thereby the projected range of future conditions, which also prevents the range of results being dominated by any one scenario.
3. Considering all available scenarios to enable a probabilistic analysis to quantify risk and uncertainty.
4. Linking scenarios with information about GCM-simulated 'natural' climate variability to express the projected scenario changes in terms of their significance, *i.e.*, whether or not the projected changes are within the range of model-simulated 'natural' climate variability.
5. Continuing to update the scenarios as GCM results are released for use.
6. Focusing on specific locations by statistical downscaling of the climate change scenarios.
7. Including results from the Canadian Regional Climate Model (CRCM). While only a limited number of climate change experiments have been undertaken with the CRCM, the results could be included with those from GCMs to give an indication of the effect of dynamical downscaling on the future climate of Saskatchewan.
8. Considering GCM performance in simulating current climate when selecting scenarios for use in impacts studies. GCMs can be ranked according to how well they simulate the baseline climate. GCM performance must be assessed at global, continental and regional scales – it is misleading and potentially dangerous to consider a GCM's performance at regional scales only. Ranking of GCM performance is not a trivial task and depends on whether the intent is to simulate just average climate or variability also. There are a number of observed baseline climatologies available for use in this sort of exercise and these too need to be examined carefully to determine which ones are considered more reliable than others.

Changes in climate variability are likely to have the largest effect on the frequency and magnitude of extreme climate events which, in turn, tend to have the largest impacts. The inclusion of changes in climate variability at a regional scale as well as changes in mean climate is not a trivial task. Statistical techniques (such as stochastic weather generators) exist which allow the perturbation of observed time series by both changes in means and variability in a simple manner. These techniques are best applied at the site scale, so one option would be to focus on specific locations in Saskatchewan. Where paleoclimate data exists, it may be used to contextualise GCM-derived climate change scenarios and also to provide valuable information about environmental responses to particular climate conditions or events. Also, a more detailed examination of the instrumental record for sites in Saskatchewan, rather than simply using the 30-year climate normal (average), would provide more information about observed climate variability and thus also help contextualise the climate scenarios.

Significant gaps in our understanding of impacts and adaption include:

- The adaptive capacity and adaptation process in agricultural systems, including options for pro-active, planned, and effective adaptation outside the range of historical experiences

- Improve crop and livestock production modeling and modeling capabilities

- Examination of impacts, adaptation and vulnerability at multiple time and space scales to allow for estimates of tipping points
- Improved and integrated modeling and assessment of the role of insects, diseases, weeds and other pests
- Effects of, and adaptation to, extreme weather and climate hazards
- Use and development of decision support tools
- Effects on agri-business and interacting effects on other sectors, especially water resources, land and resource use and management
- Availability and quality of water for agriculture, environment and other sectors
- Linkages of science and policy
- Integration of biophysical and socio-economic impacts assessments
- Monitoring of impacts and adaptation to determine a baseline and changes in vulnerability for an early warning system of adaptation needs
- Infrastructure, including the ability to move and trade commodities
- Impacts on northern Saskatchewan wetlands and northern hydrology
- Impacts on forests at risk of drought and decline
- Impacts and adaptation options for ecological management of water bodies
- Impacts and management options for protected areas
- Uncertainties in future stream and river flows

Adjustment to policy, management practices and decision-making processes

The people of Saskatchewan have historically managed their water resources while maintaining a healthy aquatic environment because there has been a relatively abundant supply of high quality water to meet the needs of communities and the economy. However, fluctuating water supplies in recent years have stressed the need to make some major shifts in our approach to managing this renewable, but finite, resource. Uncertain water supplies could require major innovations in planning and managing how water is allocated, stored, used and distributed. Integrated basin management of the South Saskatchewan River across both Alberta and Saskatchewan and for smaller watersheds in Saskatchewan is the preferred adaptation method for dealing with these uncertainties. Integrated basin management plans with apportionment powers, enforceable land use controls and agricultural management incentives may need to be implemented to deal with rapid changes and increased uncertainties in water management designs.

For the major rivers draining from Alberta into Saskatchewan, more efficient water use for irrigation or a reduction in irrigated acreage in Alberta could compensate for the reduced water availability, which is due mainly to reduced mountain snowmelt. Current minimum tillage and continuous cropping systems are resilient for most climate changes to agricultural water resources. Infrastructure will have difficulty keeping up with this level of change unless agricultural land management is used to compensate for changes in hydrology. New crop varieties and tillage methods which are able to leave some water for runoff to natural ecosystems will need to be devised. Drainage of wetlands may have to be reversed to limit high spring stream flows and wetland/lake levels.

We have many adaptation options, and some alternative choices about future ecosystems, but it will not be possible to maintain Saskatchewan's ecosystems as they were or as we know them now. The new climate-driven reality is that biodiversity managers need to think of themselves not as practitioners of preservation, but as "creation ecologists", since antecedent landscapes can no longer be effectively targeted. We have options, but the past is not one of them. Passivity in the face of impacts may shrink our ecosystem options, particularly in Prairie forests. However, active management entails some risk and expense. Whatever options we choose, the future ecosystems that result from climate change in Saskatchewan will be unprecedented.

Institutional adaptive responses to the soil degradation crisis of the 1980s-90s have reduced sensitivity of soil landscapes to climate over a large area. Soil conservation practices can be defeated, however, by extreme climatic events and especially consecutive years with droughts. Other institutional mechanisms are required to provide rewards and incentives for adaptive soil and crop management practices that reduce vulnerability to climate change.

Sustainable growth in agricultural productivity requires best management practices, with adaptive components, to deal with climate change and other compounding effects. Adaptation needs to be proactive, effective, innovative, and strategic, sometimes include changes to management and policy regimes. Enhanced adaptation would be beneficial now. Appropriate integration of both adaptation and mitigation in agriculture is needed to ensure that they are coordinated and mutually supportive. Climate change information must be mainstreamed into strategic, operational, and policy considerations. Best management practices that enable coping with droughts and climate change include water well management, land management for soils at risk, cover crops, nutrient recovery from waste water, irrigation, enhancing biodiversity, grazing plans, and integrated pest management planning.

The adaptive capacity of the forest management community in Saskatchewan is high in terms of the ability to implement sustainable forest management. However, there is less capacity in terms of the scientific details of climate change impacts, and increasing the interactions between scientists and managers should be a priority. The concept of "embedded science" can be an effective approach to educating both managers and scientists about implementing adaptation. Considering climate change in forest management will require providing information on impacts at a scale consistent with decision-making. Forest management institutions need to be examined for the extent to which they support or hinder the development and implementation of adaptation options. Consideration of new species, assisted migration of existing species and populations, and revised tenure agreements are examples of policy changes that could assist in more effective adaptation. Local autonomy and flexibility in decision-making will become increasingly important in an environment in which conditions are changing rapidly and where the past is no longer a guide to the future.

In general, the paradigm of sustainable economic development, and increasing demands on natural resources and ecological services, have spawned policy and decision-making processes that are suitable for the planning of adaptation to climate change. Examples of relevant policies and programs include environmental farm plans, watershed basin councils, and principles of adaptive forest management and integrated water resource management. Thus there is a policy framework for an institutional adaptive response to climate change. Existing policy must be evaluated, however, in terms of how it supports adaptation or conversely fosters maladaptation by providing the wrong incentives or creating barriers to adaptation. Similarly, management practices and processes must be considered from the perspective of adaptation to embed decision making about climate change in the planning and management process. Adaptation on the farm, in the forest, and in local communities is largely achieved by municipalities and individuals working collectively in social networks and as informal institutions (*e.g.* producer co-ops). The provincial government plays a critical role in terms of facilitation and a policy framework that enables proactive and effective adaption. In Saskatchewan, adaptive capacity varies among communities, but it is generally high given our financial resources, natural capital, stable governance institutions and social capital. Capacity is only the potential to respond; however, and it must be mobilized by government. Adaptive capacity is also low in some rural and northern communities in Saskatchewan, and in some First Nations.

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