FINAL REPORT

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SUMMARY

- Impacts of climate change on grazing capacity were examined by modelling the relationships between climate and grassland production in the Canadian Prairies. Climate variables and water balance estimates were related to field measurements of production by regression analysis.
- Analysis of historic time series showed that year-by-year production was most closely related to annual actual evapotranspiration (i.e. an estimate of the amount of water evaporated over the course of the growing season).
- Analysis of geographic patterns across the Canadian prairies showed that average production was most closely related to the annual water deficit (i.e. the amount by which actual rate of evapotranspiration falls short of the potential rate determined by temperature and radiation).
- Climate and production estimates from the U.S. Great Plains were used as analogues for the warmer climate predicted for the Canadian Prairies in the 2050s. Analysis of geographic patterns including both Canadian and U.S. data showed that production could be related either to actual evapotranspiration (Model 1) or to the ratio of actual to potential evapotranspiration (Model 2). The proportion of warm-season (C_4) grasses in the plant community also had a significant effect on production in these models. A third model was taken from the literature (Model 3) to provide an independent comparison.
- Five different scenarios from general circulation models (GCMs), selected to cover as wide a range of predictions as possible, were used to simulate the warmer climate of the 2050s in the Canadian Prairies. Future climate estimates were used with the climate/production models to estimate changes in grassland production.
- On loamy soils, Model 1 predicted increases in production over most of the Canadian Prairies, while Models 2 and 3 predicted decreases. There is no obvious basis for saying which model is right. However, the most striking conclusion is that predicted changes from all three models are relatively modest. The results argue against predictions of desertification of Canadian grasslands as a result of climate change over the next 50 years. This conclusion is supported by other climate change modelling studies that have been done in the U.S. Great Plains.
- Modelling indicated that the proportions of warm-season grasses will increase with climatic warming. This could contribute to higher productivity, particularly on sandy soils where dominance by warm-season grasses is most probable.
- Results of this work were communicated to a committee of stakeholders through mailouts and a workshop in December of 2003. The workshop provided valuable feedback on the many ways in which managers of grazing land, both public and private, already adapt to year-to-year weather variation. Adaptation to long-term changes in climate and production levels will require support for grassland monitoring networks that will provide the capability to detect these changes.

ACKNOWLEDGMENTS

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1. INTRODUCTION

There is increasing evidence that global temperatures have risen over the past century, and that the probable cause is anthropogenic emissions of greenhouse gases (Houghton et al. 2001). general circulation models (GCMs) have been developed to simulate global climate processes and project changes into the future (Houghton et al. 2001). In the Canadian Prairies, temperatures are predicted to increase significantly over the coming century, while predictions for precipitation are more variable (McGinn et al. 2001, Thorpe et al. 2001, Nyirfa and Harron 2002).

Most of Canada's native grassland is found in the Prairie Provinces. Native grassland is important for conservation of biodiversity and protection of sensitive soils. It also provides a significant forage resource for the livestock sector in the region. The economic value of this resource depends mainly on its grazing capacity (the number of animals and duration of grazing that can be supported on a sustainable basis). Grazing capacity depends mainly on the annual rate of forage production. Production varies widely from drier to moister areas across the region, and fluctuates from year to year with variation in weather. The direct dependence of production and grazing capacity on weather and climate is widely recognized, and plays a significant role in management decisions by livestock producers. Therefore, the rangeland grazing industry should be one of the economic sectors most vulnerable to climate change.

While other studies in this region have assessed the impacts of climate change on arable agriculture (McGinn et al. 2001, Nyirfa and Harron 2002) and tame forage (Cohen et al. 2002), there has been limited work on native grassland. A preliminary assessment on sand dune landscapes (Thorpe et al. 2001) found conflicting evidence on the probable direction of changes in grazing capacity. The purpose of the current study was to assess the impacts of climate change on productivity of native grasslands in the Canadian Prairies.

The approach of this study was to seek climate-related patterns in empirical production data from across the Canadian Prairies. This follows a fruitful body of work from the United States in which simple regression models are used to explore geographic patterns over large areas (Sala et al. 1988; Epstein et al. 1997a, 1997b, 1998, 2002a, 2002b; Paruelo and Lauenroth 1996; Paruelo et al. 1999). Production data were obtained from existing sources to cover as wide a geographic range and as long a time-span as possible. Climate data were obtained for the same geographic and temporal ranges, and statistical relationships between production and climate were examined by regression analysis.

In addition to primary climatic parameters such as temperature and precipitation, this study used water balance models to relate climate to the control of grassland production by moisture availability. These models do a monthly accounting of ecosystem water fluxes, in which precipitation or snowmelt are added each month, the amount removed by evapotranspiration is estimated (depending on the amount of stored soil moisture and the energy-limited potential rate of evapotranspiration), and the change in soil moisture and any water surplus (i.e. runoff or deep drainage) are calculated. Water balance models have been used in a variety of previous studies to predict patterns of vegetation and levels of production (Rosenzweig 1968, Webb et al. 1978, Stephenson 1990, Frank and Inouye 1994).

One of the limitations of regression models for studying climate change is that they are only valid for the range of data used in developing them. Extrapolating outside this range, as in applying models based on contemporary data to future climates outside of the range of the data, can lead to serious errors. The approach in this study was to consider grasslands in the United States to be analogues for the future warmer climate of Canadian grasslands. Regression models were developed for combined Canadian and U.S. data, which spanned the range of future climates predicted for Canada. These models were then applied to climate change scenarios for Canadian grasslands.

2. METHODS

All climatic data were expressed as monthly values (totals for precipitation, averages for temperature). The climatic baseline was the 1961-90 normals provided by Environment Canada. Normals based on climate stations have been used to create smooth continuous data surfaces across Canada by D. McKenney of the Canadian Forest Service. These surfaces are represented by fine grids of values (0.14 degrees latitude by 0.14 degrees longitude), which are available on the website of the Canadian Climate Impacts and Scenarios project (http://www.cics.uvic.ca/scenarios/index.cgi). Monthly mean maximum temperature (Tmax), monthly mean minimum temperature (Tmin), and monthly precipitation (PPT) for a given study area were taken from the nearest McKenney gridpoint. Monthly mean temperature (Tmean) was calculated as the average of Tmax and Tmin. Use of gridded normals was found to be much simpler than applying individual climate stations to grassland study areas, and had the advantage of smoothing anomalies at individual stations. It also facilitated mapping of outputs.

Individual climate stations were used for time series analyses requiring historical data for particular years. Monthly or daily values were obtained from data archive CDs purchased from Environment Canada. In general, the nearest climate station having complete data coverage for the variables and years of interest was selected.

For certain analyses, 1961-90 normals were compared to climate data in particular years. The nearest climate station having both complete 1961-90 normals and data for the years of interest was selected. If there were stations with precipitation data only, which were nearer than the nearest complete station (i.e. with data for both precipitation and temperature), the precipitation-only stations were averaged with the complete station. Only stations for which every month had precipitation data for at least two-thirds of the years in the period of interest were used.

Future climates were obtained from the outputs of general circulation models (GCMs).
The recommended approach to addressing the uncertainty of these predictions is to examine the variability among several different scenarios. The most recent GCM outputs based on the SRES emissions scenarios were obtained from the Canadian Climate Impacts and Scenarios project (http://www.cics.uvic.ca/scenarios/index.cgi) in the winter of 2002-2003. Henderson et al. (2002) used scatterplots of temperature and precipitation to select three of these scenarios covering a range of predictions. For the current project, these three were used, plus two more that give more extreme predictions:

- CMCM2 A21– selected by Henderson et al. (2002)
- CGCM2 B22 – extreme dry

- CSIROMk2b B11 – selected by Henderson et al. (2002)
- HadCM3 A21 – extreme wet
- HadCM3 B21– selected by Henderson et al. (2002

GCM outputs from the website are expressed in terms of change from the 1961-90 baseline, for a number of future 30-year periods. Change values for the 2040-2069 period (described for convenience as the 2050s) were chosen to give a reasonable time-frame for assessment of medium-term climate change. Values for change in Tmean, Tmax, Tmin, PPT, and global radiation (not available for HadCM3 A21 and HadCM3 B21) were downloaded from the website. Values are in a coarse grid (several degrees of latitude by several degrees of longitude) specific to each GCM. To apply change values to McKenney's smooth grid of 1961-90 normals, we calculated the distance from each McKenney gridpoint to each of the four surrounding GCM gridpoints, assuming 111 km per degree of latitude and 73 km per degree of longitude. We then calculated an average of the four change values weighted inversely by distance. Weighted average change values were applied to the 1961-90 normals to calculate values for the 2050s.

For each 12-month set of climatic data (whether normals or specific years), a number of derived variables were calculated. **Growing degree-days** were calculated by using the Brooks (1943) sine-wave interpolation to generate mean daily temperatures from mean monthly temperatures, then summing the daily deviations above 5° C.

Potential evapotranspiration (PET) was calculated on a monthly basis for all months with Tmean >0° C. **PET according to the Jensen-Haise method** was calculated as described by Jensen et al. (1990). This required monthly Tmean, monthly global radiation (i.e. direct plus diffuse radiation incident on a horizontal plane at the earth's surface), Tmax and Tmin for the warmest month of the year, and station elevation. Many climatic stations do not record global radiation, and the Hadley GCMs (HadCM3 A21, HadCM3 B21) do not provide change values for this parameters. For stations recording mean daily bright sunshine hours, global radiation was estimated from bright sunshine, latitude, and Julian day, using equations given by Jensen et al. (1990). Jensen-Haise PET could not be calculated for McKenney's grid of 1961-90 normals, which does not provide global radiation or bright sunshine data.

PET according to the Baier-Robertson method was calculated following Bootsma et al. (2001). Latent evaporation for the representative Julian day of each month was calculated by Formula 1 of Baier and Robertson (1965), which requires Tmax, the difference between Tmax and Tmin, and the solar radiation at the top of the atmosphere, which can be calculated from latitude and Julian day. Latent evaporation was converted to PET by multiplying by .086 (Baier 1971). Monthly PET was obtained by multiplying the daily value by the number of days in the month. For occasional months in which the calculation gave a negative PET, it was set to zero.

Grace and Quick (1988) compared PET methods at a single prairie station (Lethbridge, AB). They found that simpler methods (such as Jensen-Haise and Baier-Robertson) gave similar PET estimates to more complex methods (which require wind speed and humidity inputs) under calm conditions, but gave lower estimates under windy conditions. Foroud et al. (1989), also using Lethbridge data, developed a method for adjusting Jensen-Haise PET for wind speed. To evaluate this method, we compared calculated Jensen-Haise PET for several stations with Penman PET values for the corresponding ecodistricts as given by http://sis.agr.gc.ca/cansis/nsdb/ecostrat/district/climate.html. This comparison suggested that the correction by Foroud et al. (1989) closely approximated Penman PET in southern Alberta, where the method was developed, but underestimated Penman PET in cooler ecoregions with lower wind speeds. In any case, most of the data sources used in the current analysis did not provide wind speed data.

Preliminary analysis was done to evaluate the effect of calculating PET by the Jensen-Haise and Baier-Robertson methods on a monthly basis. Annual totals of PET were similar whether calculated from daily or monthly values.

The **water balance** was calculated using the public version of the WATBAL model (http://www.metla.fi/hanke/3098/ewat_bal.htm). Equations were taken from the website and implemented in a spreadsheet, which allowed rapid calculation for a large number of gridpoints (approximately 5,000 in McKenney's grid in the prairie region). Inputs consisted of monthly temperature and precipitation data, monthly PET calculated by either the Jensen-Haise or Baier-Robertson method, soil water-holding capacity inferred from soil texture (De Jong and Shields 1988), and initial values for snow-on-ground and soil moisture. For analyses of climatic normals, initial snow-on-ground in January was set equal to the summed normal precipitation of fall months with Tmean <0° C (usually November and December). Initial soil moisture was adjusted iteratively to give approximately the same value at the end of the year as at the beginning. For analyses of historic time-series of climatic data, the above procedure was used to set snow-on-ground at the beginning of the time-series, and soil-moisture was set to zero. After the first year, these values were calculated continuously by the model (i.e. the value for January was calculated from the value in December). Outputs of the water balance model included monthly values for soil moisture, actual evapotranspiration (AET), water deficit (AET minus PET), and water surplus. Annual totals of variables such as AET were calculated.

Canadian grassland production data were obtained by searching for field measurements over the prairie region. The main sources were the Alberta range benchmark system (Smoliak et al. [1979] and unpublished data provided by staff of Alberta Public Lands), the Saskatchewan range benchmark system (unpublished data held by PFRA in Regina), and a variety of research projects to which we had access. A total of 52 sites were assembled, with production measurements over periods ranging from one to many years (Appendices 1 to 3). Of the 52 sites, 48 were ungrazed at the time of measurement. A few of these sites with good time series of production measurements were used for analysis of year-to-year variability in production. For most analyses, the measurements from different years at a given site were averaged.

The information sources varied in the degree to which the various forage components were measured separately or combined (see Appendix 3). The only variable that could be determined for all sites was total annual forage production (graminoids plus forbs plus browse). Browse production was apparently not measured at Antelope Creek or Matador, but these are areas with low shrub abundance, so there is probably only a small error in taking herbaceous production from these areas as total production. Almost all of the data were based on air-dry weights from a single harvest per year in late summer to fall, with subjective separation of current-year's growth from older material. This method is subject to errors in separating previous years' material, and tends to underestimate annual production because it does not account for senescence of current material through the growing season (Singh et al. 1975, Biondini et al. 1991). However, because there was no way to estimate the various sources of error, it was accepted as the standard measure for comparison. A few sites with differences in measurement methods (e.g. multiple harvests, removal of litter at the start of the season, oven-dry weights) were retained in the dataset, because there was no sign that they were outliers in the various statistical relationships developed.

Grasslands in the United States were used as analogues for the warmer future climate of the Canadian Prairies. The focus was on the Great Plains portions of Montana, North Dakota, South Dakota, Wyoming, Colorado, and Nebraska, which we knew from previous work (Thorpe et al. 2001) to cover the range of 2050s climates predicted for the Canadian Prairies. Production data were obtained from Natural Resources Conservation Service (NRCS) range site descriptions (or the newer ecological site descriptions), which were provided by NRCS staff in each state. NRCS descriptions were stratified by Major Land Resource Area (MLRAs) in most cases. MLRA 34 in Wyoming and the Nebraska Sand Hills (MLRA 65) were broken into precipitation zones. In South Dakota the information was for the West Central and Eastern Technical Guide Areas. Descriptions were obtained for loamy and sand range sites, or the closest equivalent in each region, for a total of 32 sites (Appendix 4). Data were for climax or excellent-condition communities on a given site. According to the methods given in the National Range and Pasture Handbook (NRCS 1997), production values in these descriptions represent air-dry weight of annual production of all plants, based on a single harvest at the end of the growing season. Therefore, they should be comparable to the Canadian data.

For each region represented by the U.S. data, at least three climate stations were located, and 1961-90 normals for monthly Tmean, Tmax, Tmin, and PPT were obtained from www.worldclimate.com. The only exception was MLRA 58A in Montana, where we used nominal PPT values of 254, 279, 305, 330, and 356 mm (10, 11, 12, 13, and 14 inches), which were given different production levels in the range site description.

Vegetation composition information varied, both in the Canadian and in the U.S. data. Some data sources gave quantitative biomass or percentage values by species, while others gave more general descriptions listing community dominants. The percentages of C_3 and C_4 species by biomass were calculated if possible. Otherwise, communities were assigned to the following categories on the basis of vegetation descriptions:

C_3	>80% C_3
C_3C_4	50-80% C_3
C_4C_3	50-80% C_4
C_4	>80% C_4

For some Alberta and Saskatchewan benchmark sites, there was little vegetation information, so the following generalizations were made on the basis of patterns in the sites with quantitative data: C_3C_4 on dunesands, C_3C_4 on the warmest and driest loamy sites, and C_3 everywhere else. For some analyses, C_4 and C_4C_3 were combined to a C_4-dominant category, and C_3C_4 and C_3 into a C_3-dominant category.

The main method of data analysis was multiple linear regression of grassland production on various combinations of climate or water balance variables. For some analyses, binary variables to represent presence/absence of grazing, various range sites, or various composition types were tested. Regression models were evaluated by the coefficient of determination (R^2), the statistical significance of partial regression coefficients, and checks for pattern in residuals. All of the regression models reported below were fit by linear models on untransformed data, with no evidence from residuals to indicate the need for data transformations or non-linear regression.

In cases in which externally derived models (e.g. from literature sources) were applied to data from the current analysis, models were compared by two methods:

- Comparing predicted to observed values in terms of mean deviation (observed minus expected) as a measure of bias, and absolute mean deviation as a measure of goodness-of-fit.
- Calculation of a linear regression of observed on predicted values, to generate the diagnostics given by Smith and Rose (1995): sum of squared predictive error (SSPE) as a measure of goodness-of-fit, and partitioning of this sum among a bias component (i.e. do the observed values tend to be higher or lower than the predicted values?), a consistency component (i.e. does the slope of the regression differ from 1.0?), and an unexplained component.

Spatial results for the prairie region were mapped using the MapMaker GIS package. The datum was NAD 1983, and the projection was Lambert Conformal, with standard parallels at 50.8333° North and 58.16666° North, and origin at 105.59583° West, 50.8333° North. Isolines were created by the 3D surface utility in Mapmaker, using inverse distance weighting of the nearest values in four directions. Small polygons were edited out to improve map clarity. Maps were clipped to the boundaries of the Prairie Ecozone (Ecological Stratification Working Group 1995) using a digital map obtained from http://sis.agr.gc.ca/cansis/nsdb/ecostrat/index.html.

3. RESULTS

3.1 Year-to-year variation in production

The best dataset for year-to-year variability in grassland production is from the Agriculture Canada Research Substation near Manyberries in southeastern Alberta (Appendix 1). Smoliak (1986) reported annual production data for an area of moderately grazed *Stipa-Bouteloua* grassland from 1930 to 1983, with only a few gaps during World War II. Sampling has continued at this site to the present (Walter Willms, Agriculture and Agri-food Canada, personal communication). There was a climate station at the Substation from 1928 to 1990. However, bright sunshine data, needed for estimation of global radiation for Jensen-Haise PET, were available only from 1951, and the station apparently ceased to function partway through 1990. Therefore, most analysis was done on the 39-year period from 1951 to 1989. Even in this sequence, there were a few missing values, which were replaced by estimates. The water balance was calculated continuously through this period, using both the Jensen-Haise and Baier-Robertson methods for PET.

The closest relationships were between P, the annual production (kg/ha), and annual AET (mm):

PET METHOD	EQUATION	SIGNIFICANCE OF COEFFICIENT	R^2
Jensen-Haise	P = -232 + 1.92 * AET	0.000	65.5%
Baier-Robertson	P = -239 + 1.94 * AET	0.000	69.4%

Because the water balance based on Baier-Robertson PET gave a somewhat better relationship between production and AET (Figure 1), and requires fewer inputs (no bright sunshine/global radiation data), it was used for subsequent analysis. Predicted production values from this relationship clearly track the year-to-year variations in measured production (Figure 2).

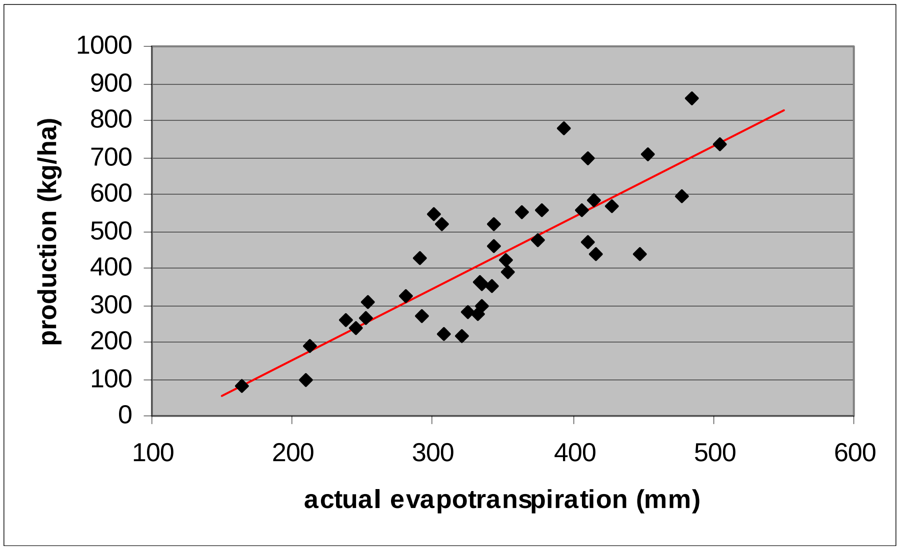

Figure 1. **Relationship between production and actual evapotranspiration for individual years from 1951 to 1989 at Manyberries, AB.**

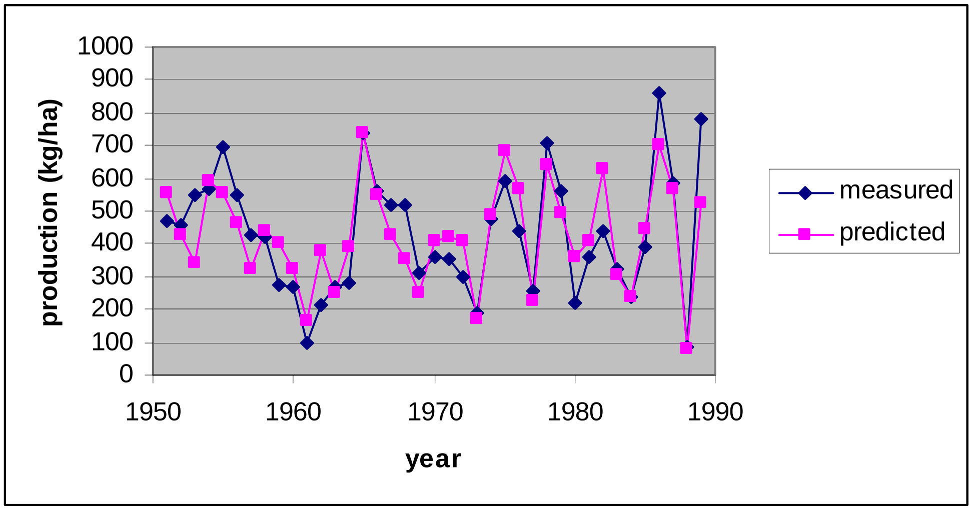

Figure 2. **Measured production at Manyberries, AB, from 1951 to 1989, and production predicted from regression on actual evapotranspiration (AET).**

Regressions of production on other independent variables gave poorer relationships. The best of these was the annual water deficit (AET – PET).

INDEPENDENT VARIABLES	**R^2**
April soil moisture	21.1%
May soil moisture	37.0%
June soil moisture	40.5%
July soil moisture	44.2%
August soil moisture	30.0%
annual PPT	56.2%
annual PET	20.1%
annual (AET - PET)	55.8%

In addition, the best of the regression models developed by Smoliak (1986) using the Manyberries data from 1930 to 1983 were recalculated using the current dataset. Most of them gave poorer regressions than the AET relationship. Independent variables for which the partial regression coefficient was not statistically significant at p=0.05 are indicated by n.s.:

INDEPENDENT VARIABLES	**R^2**
April to July PPT	52.6%
Sept + April to July PPT	67.4%
July PPT, June Tmean	43.3%
June PPT (n.s.), July PPT, June Tmean	47.9%
June PPT (n.s.), July PPT, May Tmean (n.s.), June Tmean	51.6%

The best of the above regressions used the precipitation total from the previous September and the current April, May, June, and July, giving R^2 similar to the AET relationship. This illustrates the importance of fall precipitation for production in the coming year. One strength of the water balance method is that it explicitly accounts for the contribution of fall rain and winter snowfall to the moisture available to plants in spring. This can be seen from an analysis in which the connections between years were removed from the water balance model (i.e. soil moisture and snow-on-ground were initialized at the start of each year). This reduced the R^2 of the regression based on Jensen-Haise PET from 65.5% to 53.7%.

Because of the evidence of carryover effects from previous years, regressions were tested for autocorrelation, by including the previous year's value of an independent variable as an additional predictor. None of these regressions gave significant coefficients.

The approach developed from the Manyberries data was tested on other sets of time-series data, all of which were much shorter. The Antelope Creek Ranch is an experimental area near Brooks, Alberta (Appendix 1). Production data from grazed and ungrazed fields were available for 1988 through 2002 (Alberta Public Lands 2001; Barry Adams, Alberta Public Lands, personal communication). However climate data were not as continuous. The data came from climate stations at Brooks: Brooks AHRC to November 1988, Brooks thereafter, with Brooks North used to supply occasional missing values for monthly precipitation. Analysis was possible for 1988, 1989, 1990, 1996, 1997, 1998, 1999, and 2000. The water balance was calculated using Baier-Robertson PET, and production (P, kg/ha) was related to annual AET (mm):

FIELD	**REGRESSION**	**SIGNIFICANCE OF COEFFICIENT**	**R^2**
ungrazed	P = -1111 + 6.70 * AET	0.001	86.2%
grazed	P = -1686 + 9.50 *AET	0.003	78.4%

Similar analyses were done for several Alberta range benchmarks sites in the parkland region, where production data from 1989 through 2002 were available (Harry Loonen, Alberta Public Lands, personal communication). Climate data were available only up to 2000, and it was difficult to find nearby climate stations with complete records for the period of interest. Seven study areas were clustered together (Parkland-Dvr, Parkland-Mtl, Parkland-Rbt, Parkland-Hwe, Parkland-Kch, Parkland-Kpg, and Parkland-Mlr) (Appendix 1), and climate data were used from six surrounding stations (Paradise, Coronation, Kinsella Ranch, Fabyan, Alliance, and Brownfield). For another study area that was somewhat separated (Parkland-Vty), four climate stations were used (Coronation, Sibbald, Scotstown, and Kerrobert).

Regression of production (P, kg/ha) on AET (mm, based on Baier-Robertson PET) was in some cases improved by not using the first few years of the data record. This is probably related to vegetation changes following the initial establishment of the protected benchmark site. In the following summary, these improved regressions are shown. Three of the study areas are not shown because regression coefficients were not statistically significant at p=0.05. Four of the remaining five showed a significant positive regression between production and AET, but at Parkland-Mtl the relationship was inexplicably negative.

STUDY AREA	**REGRESSION**	**SIGNIFICANCE OF COEFFICIENT**	**R^2**
Parkland-Kpg, 1992-2000	P = -293 + 5.80 * AET	0.037	48.5%
Parkland-Mtl, 1989-2000	P = 5419 – 7.68 * AET	0.048	33.7%
Parkland-Dvr, 1994-2000	P = -276 + 10.5 * AET	0.036	61.8%
Parkland-Rbt, 1989-2000	P = -783 + 6.70 * AET	0.009	51.1%
Parkland-Vty, 1993-2000	P = 1057 + 5.35 * AET	0.008	72.2%

3.2 Geographic variation in production in Canadian grasslands

Analysis of geographic patterns of grassland production across the Canadian Prairies was based on a dataset of 52 sites, each of which had annual production data for one to many years (Appendices 1 to 3). Production data were averaged over the years of measurement for this analysis. Averages were related to 1961-90 normal climate data and variables derived from them, based on McKenney's smooth grid surface. Year-by-year climatic data for the period of production measurement were also used, to account for the possibility that measurements were made in unusually wet or dry years relative to the 1961-90 normals. Period-of-measurement data were taken from the nearest climatic station and averaged over years, and the ratio to the normal value for the study area was calculated.

A variety of regression models for prediction of annual production (P, kg/ha) were tried, including the following:

INDEPENDENT VARIABLES*	R^2
April soil moisture	11.9%
May soil moisture (n.s.)	6.7%
June soil moisture	8.6%
July soil moisture	10.9%
August soil moisture	8.7%
April to August soil moisture	10.1%
May to June soil moisture (n.s.)	7.2%
PPT	27.5%
AET	25.7%
period-of-measurement AET	30.0%
PPT, GDD	40.8%
AET, GDD	40.4%
AET (n.s.), PET	45.0%
AET/PET	40.6%
(AET-PET)	44.4%
(AET-PET), AET ratio	51.3%

*PPT – annual precipitation (mm)
AET – annual actual evapotranspiration (mm)
PET – annual potential evapotranspiration (mm)
GDD – annual growing degree-days
Period-of-measurement AET – AET during period of production measurement (mm)
AET ratio - ratio of AET during period of production measurement to normal AET

The last two models were the most promising. Removal of three outliers in the model using AET-PET, and two in the model using AET-PET and AET ratio, resulted in improved regressions:

EQUATION	SIGNIFICANCE OF COEFFICIENTS	R^2
P = 3352 + (6.13 * [AET-PET])	DEFICIT: 0.000	60.4%
P = 1895 + (5.50 * [AET-PET]) + (1178 * AET ratio)	DEFICIT: 0.000 AET RATIO: 0.025	58.9%

The best regression related annual production to annual water deficit (AET-PET) based on 1961-90 normals. A good regression was also obtained using two independent variables: water deficit, and the ratio of AET during the period of production measurement to normal AET. The first model, relating annual production to annual water deficit (AET-PET, based on 1961-90 normals) gave a slightly higher R^2, and has the advantage of being simpler. It suggests that most of the variation in production across the prairie region can be explained by the geographic pattern of long-term average water deficit. However, the second model, relating production to water deficit and the ratio of AET during the period of production measurement to normal AET, suggests that weather during the period of measurement had a small but significant effect on regional production patterns, in addition to the effect of normal deficit. Both of these models were better than simple ones based on PPT or AET.

Figure 3 shows the spatial distribution across the Canadian Prairies of annual production predicted by the regression on water deficit. Maps were prepared by calculating the water balance for each gridpoint on McKenney's smooth data surface of 1961-90 normals (see Methods), then applying the regression to water deficit values. Separate maps are shown for loam and sand, because the water balance was different for soils with different water-holding capacity. It should be noted that the maps in Figure 3 do not show the production that actually occurs at a given point. Rather, they show the production that would occur if there were native grassland on loam or sand at that point.

This analysis has not directly considered the effects of range site and grazing impact on production. The effect of range site is indirectly included through the dependence of water-holding capacity on soil texture. Monthly water surpluses (usually occurring during spring snowmelt) are more frequent and larger in coarse-textured soils because of their lower water-holding capacity. This means that more of the input from precipitation is lost (presumably to deep drainage) on these soils, reducing the effective water availability to plants in a given climate.

Grassland production is also known to vary with the degree of grazing impact. Four of the 52 study areas were being grazed at the time of sampling: Manyberries, Grazed; Antelope Creek, Grazed; Dundurn Sand Hills, and Great Sand Hills (Appendix 2). The other 48 were all fenced from grazing to serve as research areas or benchmark sites. Most of these were probably either long-ungrazed or only lightly grazed up to the time that that the area was fenced.

To search for any additional effect of site or grazing, residuals from the two best regressions were compared to presence/absence of loamy, sandy, sand, or burnout sites, and of current grazing. T-tests showed no significant differences in residuals in relation to these variables. Similarly, inclusion of binary variables in regressions gave no significant coefficients. A continuous variable for water-holding capacity also showed no relationship to the residuals. In most cases, there were simply not enough study areas in the various categories of site or grazing impact to reveal their effects.

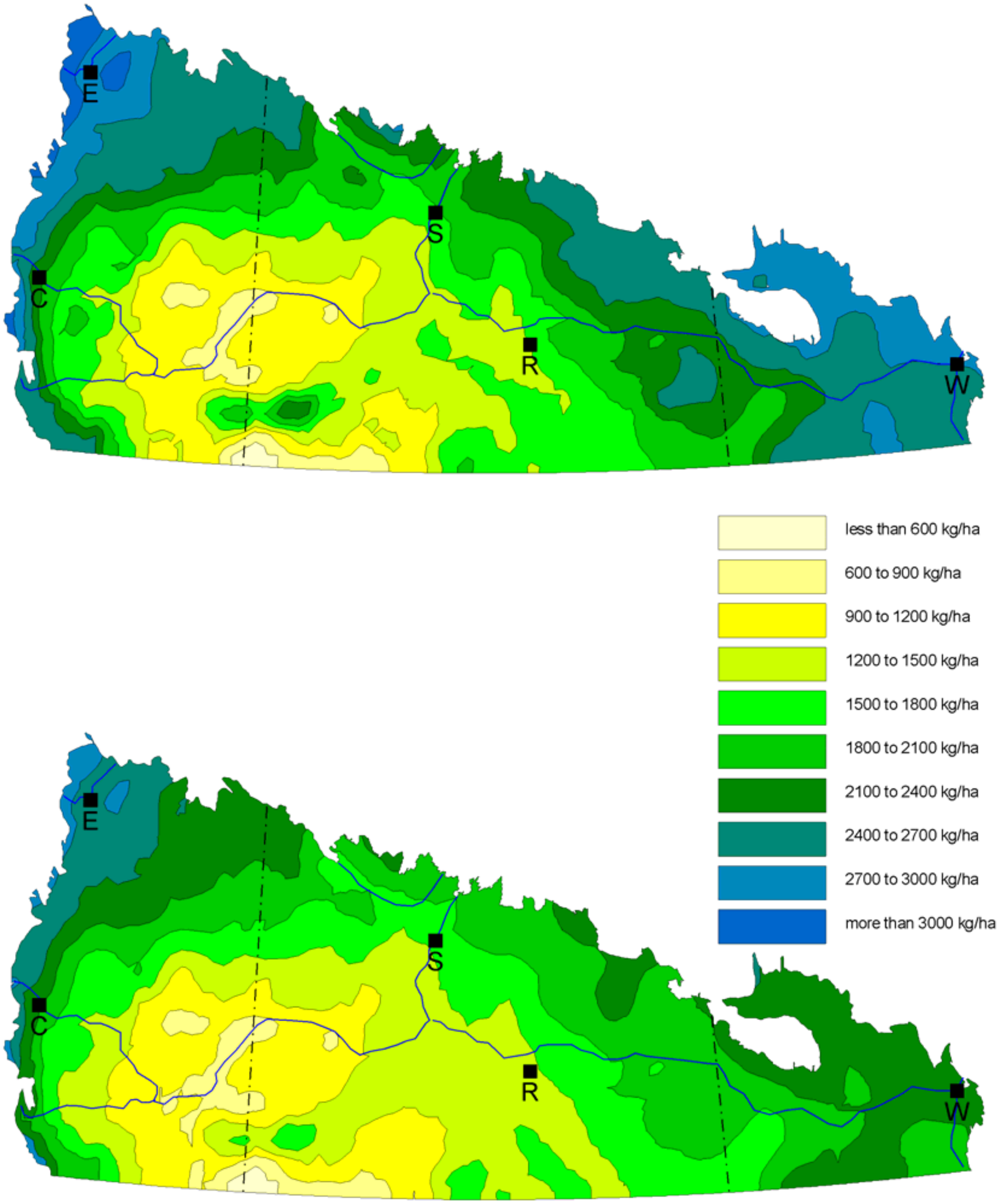

Figure 3. **Annual production of native grassland in the Canadian prairies on loam (top) and on sand (bottom), predicted from 1961-90 water deficit.** Provincial boundaries, major rivers, and major cities (Edmonton, Calgary, Saskatoon, Regina, Winnipeg) are shown for reference.

3.3 Production/climate relationships in U.S. and Canadian grasslands combined

Relationships were developed in Section 3.2 for the current production/climate relationships in Canadian grasslands. However, because these relationships were developed from current Canadian data (1961-90 climate normals, and production measurements from roughly the same period), extrapolation to future climates is questionable. To illustrate this point, the best relationship developed from the Canadian data, predicting production from water deficit, was used to predict production from U.S. climate data, which can be considered to be analogues for the warmer future climate predicted for Canada. Diagnostics for application of this model (Smith and Rose 1995) are shown in Table 1, with the same diagnostics for application back to the original Canadian data for comparison.

Table 1. Diagnostics for application of model for predicting grassland production from water deficit to Canadian and U.S. data.

	Canadian data	U.S. data
mean deviation (kg/ha)	-16	1953
mean absolute deviation (kg/ha)	406	1953
Theil's measure of distance	0.21	0.80
sum of squared prediction error	14,092,455	129,922,847
• consistency component	0.01	0.01
• bias component	0.00	0.94
• unexplained component	0.99	0.05

Predictions from the model fitted the U.S. data poorly, as shown by much higher absolute deviation, Theil’s measure of distance, and sum of squared prediction error. Higher mean deviation, and a higher bias component in the sum of squared prediction error, showed that the main reason for the poor fit was bias in the direction of underestimation of production for U.S. grasslands. While this model fitted the current Canadian production/climate relationship reasonably well, it was inappropriate for application to the significantly warmer climates found in the U.S., and by analogy to the warmer future climates predicted for Canada.

In order to develop more appropriate models, analysis was done on a dataset which combined the 52 Canadian study areas with 32 U.S. range site descriptions. The same types of data were available as in the analysis in Section 3.2: annual grassland production, 1961-90 climate normals, and variables derived from those normals such as growing degree-days and water balance estimates. The following regressions for prediction of production were tried on this combined dataset.

INDEPENDENT VARIABLES	**R^2**
PPT	49.7%
PPT, GDD (n.s.)	50.6%
AET	49.5%
AET, PET (n.s.)	50.3%
AET, (AET-PET) (n.s.)	50.3%
(AET-PET)	8.2%
(AET/PET)	23.0%

This showed that the variation in production in the combined dataset was primarily related to annual precipitation or actual evapotranspiration. Inclusion of thermal variables (GDD, PET), either as additional independent variables or in moisture indices (AET-PET, AET/PET), did not improve the regressions.

In examining residuals from these regressions, another factor that emerged was the proportions of cool-season (C_3) and warm-season (C_4) grasses. Because of differences in water-use efficiency between C_3s and C_4s, their proportions may affect the relationship between production and climate. While ideally this effect would be analyzed using the percentage of C_4s as a continuous variable, the data only allowed the assignment of sites to broad dominance categories (see Methods). This factor was not considered in the analysis of Canadian grasslands (Section 3.2), because they are almost completely dominated by C_3s. Regressions were attempted using four categories for species composition (C_4, C_4 C_3, C_3 C_4, and C_3) as independent variables, but these gave nonsignificant partial regression coefficients. Only the regressions using the simple categorical variable of C_4 dominance (i.e. 1 for C_4 and C_4 C_3, 0 for C_3 C_4 and C_3) were successful.

INDEPENDENT VARIABLES	**R^2**
PPT, C_4 dominance	54.8%
PPT, GDD (n.s.), C_4 dominance	55.3%
AET, C_4 dominance	54.6%
AET, PET (n.s.), C_4 dominance	55.0%
(AET-PET), C_4 dominance	41.5%
(AET/PET), C_4 dominance	50.4%

Either annual precipitation or annual evapotranspiration with C_4 dominance gave the best regressions. Addition of thermal variables (GDD, PET) as independent variables gave non-significant coefficients. However, use of thermal variables in moisture indices (AET-PET, AET/PET), with C_4 dominance, gave significant regressions, with the model using AET/PET yielding a better fit. Two regressions were selected for modelling of climate change: AET with C_4 dominance (Figure 4), and AET/PET with C_4 dominance (Figure 5). Removal of outliers (four from the first, three from the second) gave the following final regressions:

EQUATION	**SIGNIFICANCE OF COEFFICIENTS**	**R^2**
MODEL 1: $P = -447 + 5.74*AET + 519* C_4$ dominance	AET – 0.000 C_4 dominance – 0.000	62.8%
MODEL 2: $P = -64 + 3184*(AET/PET) + 1099* C_4$ dominance	AET/PET – 0.000 C_4 dominance – 0.000	57.6%

P - annual production (kg/ha),
AET - annual actual evapotranspiration (mm),
PET - annual potential evapotranspiration (mm)
C_4 dominance - binary variable for dominance by C_4s.

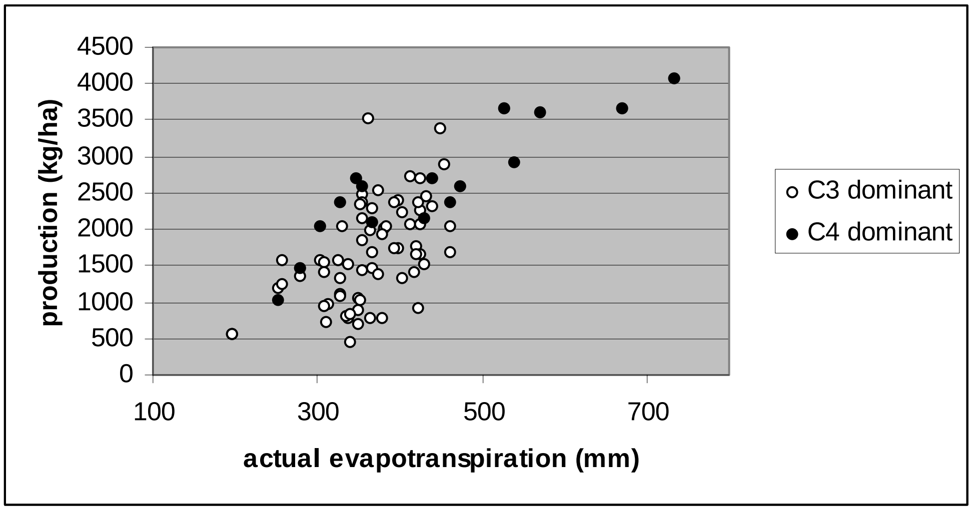

Figure 4. Annual production in relation to actual evapotranspiration and dominance by C3s or C4s, for native grasslands in the Canadian Prairies and the U.S. Great Plains.

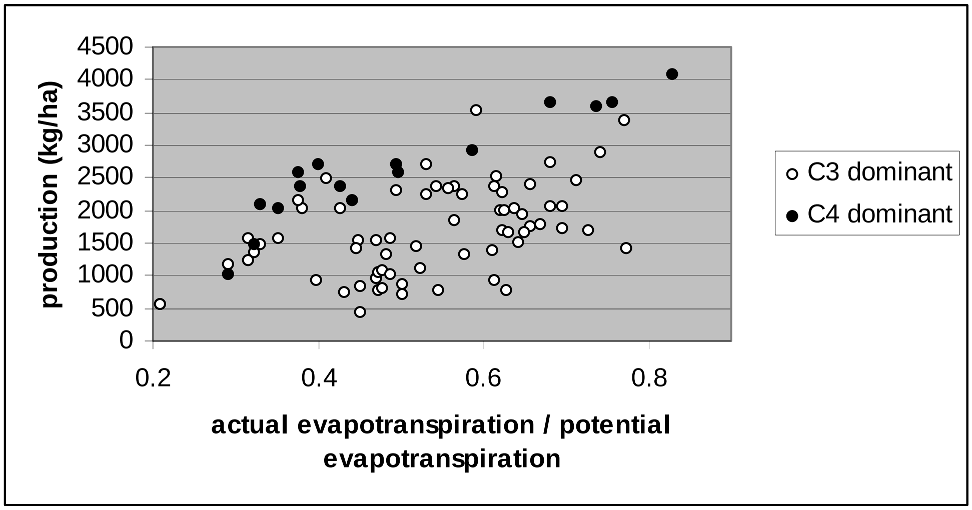

Figure 5. Annual production in relation to the ratio of actual to potential evapotranspiration and dominance by C3s or C4s, for native grasslands in the Canadian Prairies and the U.S. Great Plains.

It would be possible to apply these models by assuming a constant pattern of C_4 dominance. However, this is unrealistic, because it is known that C_4 dominance shows definite trends with climate, and therefore would be expected to shift with climate change. Therefore, the relationships between C_4 dominance and climate were explored using the combined Canadian and U.S. dataset. The stepwise logistic regression procedure in SPSS was used to predict C_4 dominance from a variety of climate and site variables. The best model used two independent variables: growing degree-days (GDD) and a binary variable for the presence of sand (i.e. 1 for sand, 0 for finer soil textures). If this expression is positive, then C_4 dominance is indicated; if negative, C_3 dominance.

EQUATION	**SIGNIFICANCE OF COEFFICIENTS**	**R^2 (Cox & Snell)**	**R^2 (Nagel-kerke)**
-25.049 + (0.010 * GDD) + (7.070 * SAND)	GDD - 0.002 SAND – 0.006	54.8%	88.1%

To provide a totally independent production prediction for comparison purposes, models developed by Epstein et al. (1997a) were applied to the climatic data for the combined Canadian and U.S. study areas. These models were developed from a large dataset of NRCS range descriptions in the U.S. Great Plains, and predicted the production of C_3s and of C_4s. For the current analysis, C_3 and C_4 production were added to give total production. Because Canadian data were not used in development of these models, there may be some error in applying them to current production in Canada. However, data from Montana and North Dakota are very close to the range of climates found in Canadian grasslands, so the risk of extrapolation is relatively small.

EQUATION	**SIGNIFICANCE OF COEFFICIENTS**	**R^2**
C3PROD = 178.73 – 11.24*MAT + 0.322*MAP - 0.241*SAND	MAT – 0.0001 MAP – 0.0419 SAND – 0.0001	67%
C4PROD = -180.29 + 5.425*MAT + 5.53*MAP + .595*SAND – 1.353*CLAY	MAT – 0.0001 MAP – 0.0001 SAND – 0.0001 CLAY – 0.0009	81%

C3PROD – annual production of C_3s (kg/ha)
C4PROD – annual production of C_4s (kg/ha)
MAT – mean annual temperature (˚C)
MAP – mean annual precipitation (cm)
SAND – sand content of soil (%)
CLAY – clay content of soil (%)

Diagnostics in Table 2 show that the fit of the Epstein model to the current dataset was nearly as good as that of the regression models calculated directly from this dataset, with low contributions to total error attributable to bias or lack of consistency. The Epstein model showed a small bias in the direction of over-estimation of production.

Table 2. Diagnostics for application of the model of Epstein et al. (1997a) to the combined U.S. and Canadian dataset, compared to two models developed by regression analysis on this dataset.

	MODEL 1: AET & C_4 dominance	MODEL 2: AET/PET & C_4 dominance	MODEL 3: Epstein
mean deviation (kg/ha)	11	21	-89
mean absolute deviation (kg/ha)	437	454	502
Theil's measure of distance	0.19	0.20	0.21
sum of squared prediction error	24,300,769	26,681,120	30,935,992
• bias component	0.00	0.00	0.02
• consistency component	0.00	0.00	0.00
• unexplained component	1.00	1.00	0.98

3.4 Production in future climates

Production in future climates was explored by applying the models developed in Section 3.3 to climate predicted for the 2050s by five scenarios (see Methods).

C_4 dominance was predicted using the regression based on growing degree-days and a binary variable for presence of sand (1 for sand, 0 for loam). This was calculated for both sand and loam sites for each McKenney gridpoint, for 1961-90 and for each of the 2050s scenarios. A binary variable for C_4 dominance was then used in Models 1 and 2 (see Section 3.3) for prediction of annual grassland production. Model 3 (the Epstein model) did not use this variable, but required textural percentages. Sand sites were assumed to be 85% sand and 5% clay, while loam sites were assumed to be 40% sand and 15% clay. These models (based on Canadian plus U.S. data) generated production estimates for 1961-90 and for the 2050s. However, the 1961-90 estimates from these models often did not fit the current production levels as well as models developed using Canadian data only (see Section 3.2). Rather than use the production estimates from Models 1, 2, and 3 directly, the percent change in production from 1961-90 to the 2050s was calculated for each model. This was then applied to the current production according to the model which gave the best fit to current data, based on 1961-90 water deficit. This is analogous to the standard approach used to apply scenario results to climatic data, in which change values from the scenarios are applied to actual 1961-90 normals (http://www.cics.uvic.ca/scenarios/index.cgi).

In order to explore the results of the five scenarios, climatic variables, water balance estimates, and predicted grassland production were extracted for a sample of gridpoints. This sample was selected by taking the gridpoints nearest to the 64 intersections of whole degrees of latitude and longitude falling within the Prairie Ecozone. Average changes were calculated for this sample (Tables 3 to 5).

The five scenarios all predicted substantial increases in the temperature-dependent variables (GDD and PET), with only modest differences among scenarios (Table 3). Changes in annual precipitation were small for all scenarios. However, seasonal precipitation showed larger changes, which were more variable among the five scenarios. Winter and spring precipitation tended to increase, while summer precipitation tended to decrease. Changes in estimated AET tracked those in annual precipitation, and again were small for all five scenarios.

Table 3. Percent change from 1961-90 to the 2050s in climatic variables and water balance estimates, averaged over 64 grid-points in the prairie region.

	Scenario				
	CGCM2 A21	**CGCM2 B22**	**CSIROMk2b B11**	**HadCM3 A21**	**HadCM3 B21**
Growing degree-days	47	36	33	37	36
Precipitation, annual	0	0	2	6	2
Precipitation, Dec-Jan-Feb	4	3	13	21	21
Precipitation, Mar-Apr-May	15	14	17	7	18
Precipitation, Jun-Jul-Aug	-8	-7	-8	-2	-10
Precipitation, Sep-Oct-Nov	-6	-5	-1	11	-5
Potential evapotranspiration	21	20	16	17	18
AET on loam	0	0	3	6	2
AET on sand	-2	0	3	4	-2

The predicted percentage of the area with C_4 dominance was virtually zero for 1961-90 (Table 4), consistent with actual patterns in the region. The model predicted some increase in C_4 dominance on loamy soils for the warmest 2050s scenario (CGCM2 A21), but not for the others. On sand, however, all scenarios showed a shift to extensive C_4 dominance.

Table 4. Percentage of points at which C4 dominance was predicted, in a sample of 64 gridpoints in the prairie region.

		scenario				
	1961-90	**CGCM2 A21**	**CGCM2 B22**	**CSIROMk2b B11**	**HadCM3 A21**	**HadCM3 B21**
loam	0	19	0	0	0	0
sand	2	100	92	92	100	97

Grassland production on loam showed a small increase for Model 1 for most scenarios, and modest decreases for Models 2 and 3 (Table 5). Production on sand showed significant increases for Models 1 and 2, and small decreases for Model 3. The increases on sand for Models 1 and 2 are attributable to the predicted shift to C_4 dominance over most of the area, which results in higher predicted production in these models. For all of these changes, the five scenarios were fairly similar.

Table 5. Percent change from 1961-90 to the 2050s in estimates of annual grassland production, averaged over 64 grid-points in the prairie region.

	Scenario				
	CGCM2 A21	CGCM2 B22	CSIROMk2b B11	HadCM3 A21	HadCM3 B21
Model 1, loam	5	0	3	7	2
Model 2, loam	-8	-17	-12	-10	-14
Model 3, loam	-11	-9	-6	0	-4
Model 1, sand	29	29	33	36	28
Model 2, sand	44	42	47	52	44
Model 3, sand	-9	-8	-5	0	-3

The five scenarios gave similar results in most cases. Therefore, for mapping of results over the whole region, one of the scenarios was chosen to represent the changes. The CSIROMk2b B11 scenario tended to be intermediate among the five scenarios, particularly for production estimates, so maps were produced for this scenario.

Figure 6 shows the large increase in growing degree-days from 1961-90 to the 2050s. Figure 7 shows the small change in annual precipitation over this period.

Based on the 1961-90 climate, C_4 dominance on sand soils is predicted for a small part of the region (Figure 8). This is consistent with the observed pattern of C_3 dominance over virtually all of the Canadian Prairies. However, for the 2050s according to the CSIRO scenario, C_4 dominance on sand is predicted over most of the region (Figure 8). On loam soils, C_4 dominance is predicted nowhere in 1961-90, and for only a small area in southern Manitoba in the 2050s (map not shown).

Figures 9 and 10 show the predicted annual production on loam soils for 1961-90 and for the three models for the 2050s. Model 1 (based on AET and C_4 dominance) shows only slight changes from current patterns of production. Model 2 (based on AET/PET and C_4 dominance) and Model 3 (based on Epstein's model) show decreases (i.e. larger areas of low-productivity classes). However, the changes from all three models are modest, with the general patterns of production levels across the region unchanged. The variable for C_4 dominance in Models 1 and 2 had little effect on these results, because no shift in the pattern of C_4 dominance was predicted on loam soils.

In the case of sand soils (Figures 11 and 12), Models 1 and 2 predict significant increases in production, whereas Model 3 predicts little change. This is because in Models 1 and 2, production increases with C_4 dominance, which is predicted to expand over most of the region in the 2050s on sand soils (Figure 8). The Model 3 result is not directly affected by this predicted change in C_4 dominance.

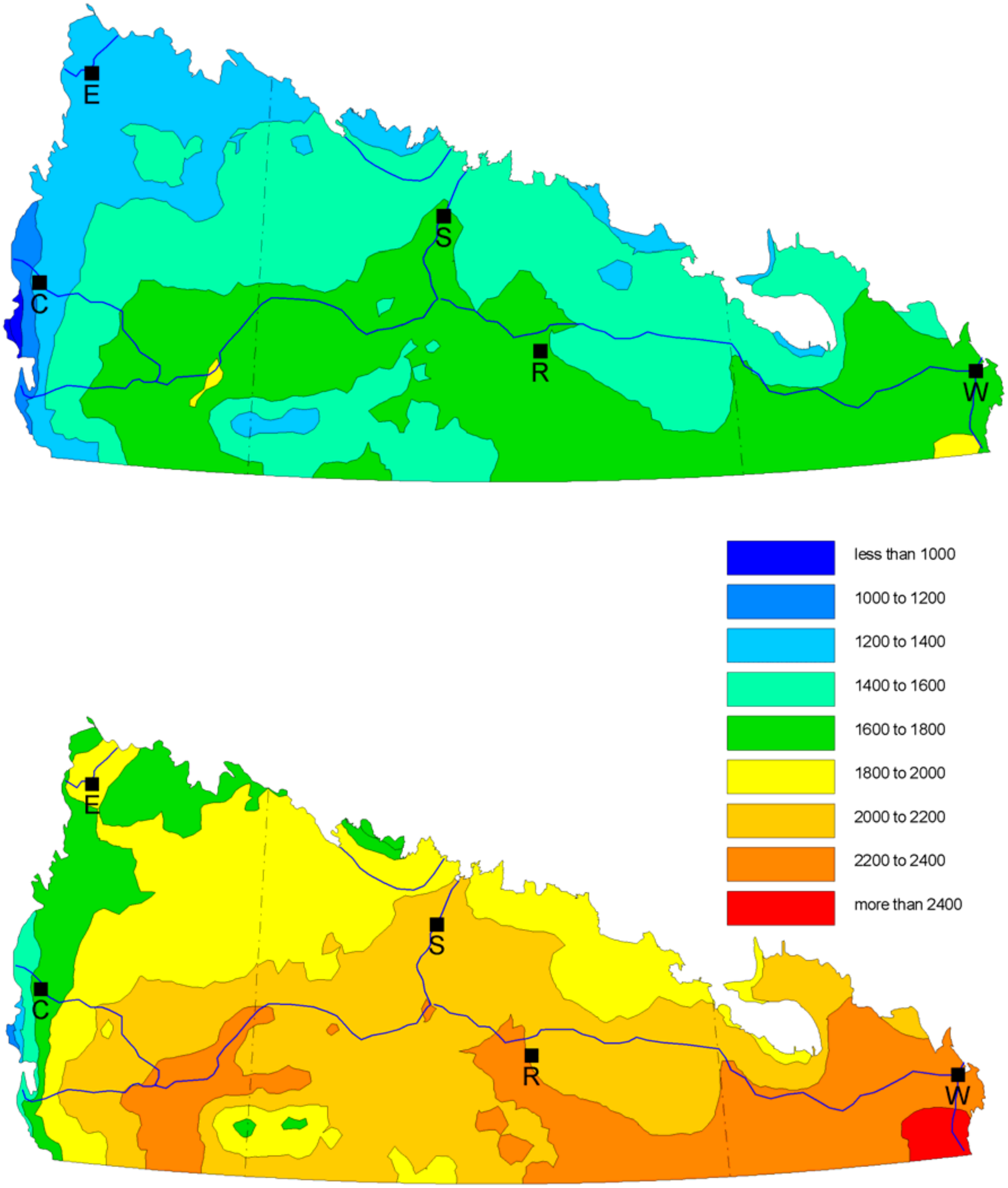

Figure 6. Growing degree-days in the Canadian prairies, in 1961-90 (top) and in the CSIROMk2b B11 scenario for the 2050s (bottom). Provincial boundaries, major rivers, and major cities (Edmonton, Calgary, Saskatoon, Regina, Winnipeg) are shown for reference.

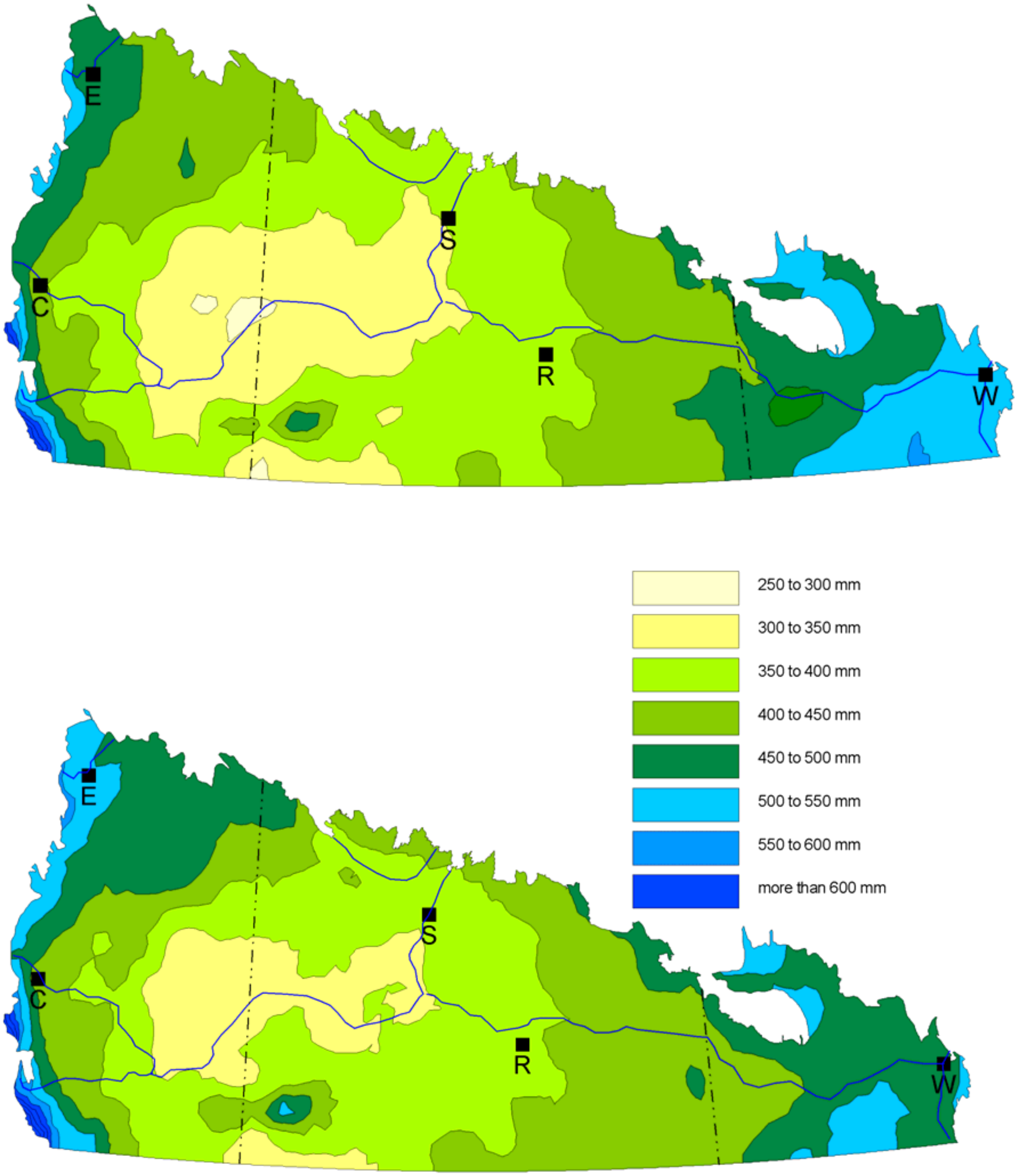

Figure 7. **Annual precipitation in the Canadian prairies, in 1961-90 (top) and in the CSIROMk2b B11 scenario for the 2050s (bottom).** Provincial boundaries, major rivers, and major cities (Edmonton, Calgary, Saskatoon, Regina, Winnipeg) are shown for reference.

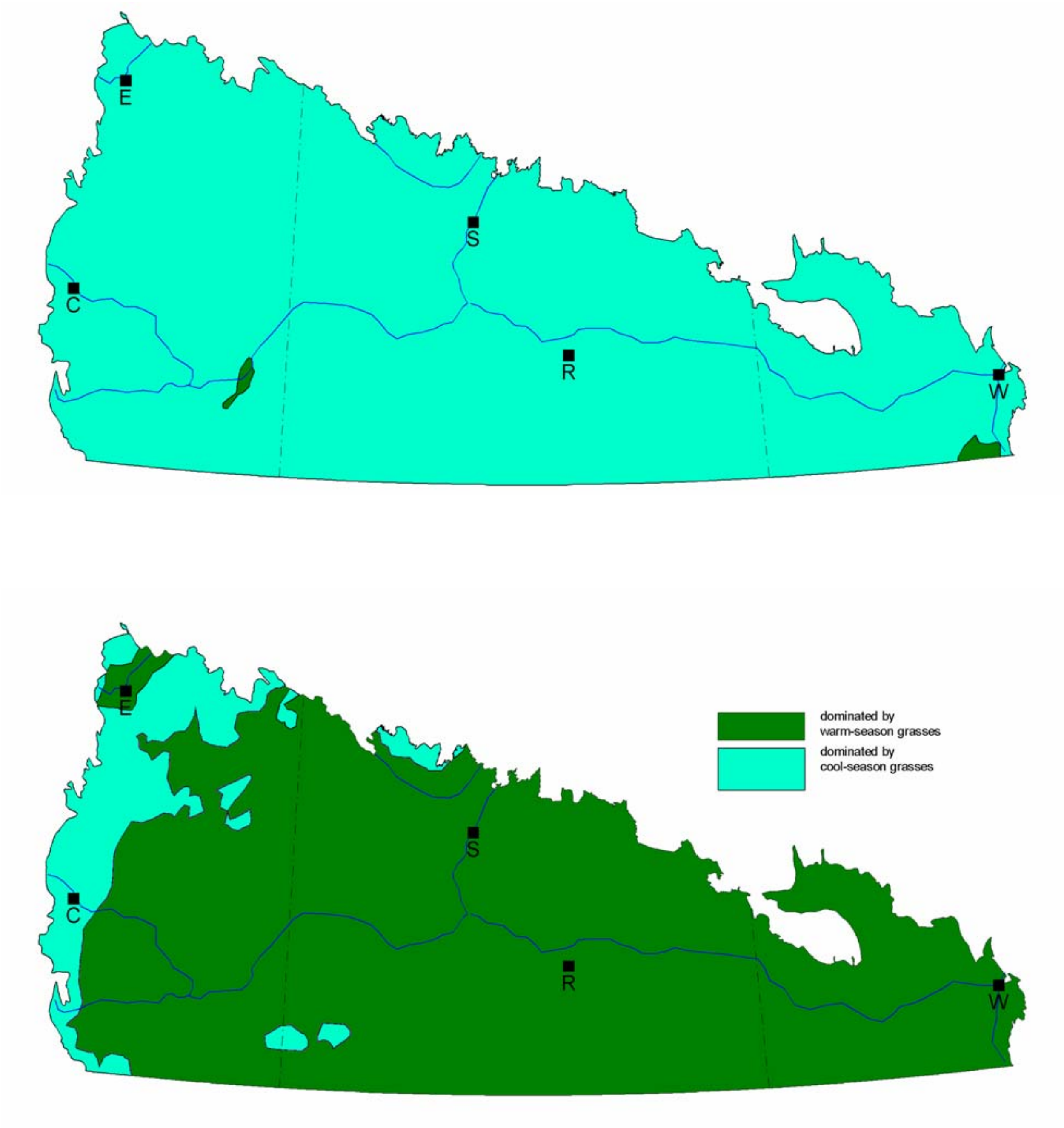

Figure 8. **Area predicted to be dominated by warm-season (C4) and cool-season (C3) grasses on sand in 1961-90 (top) and in the CSIROMk2b B11 scenario for the 2050s (bottom).**

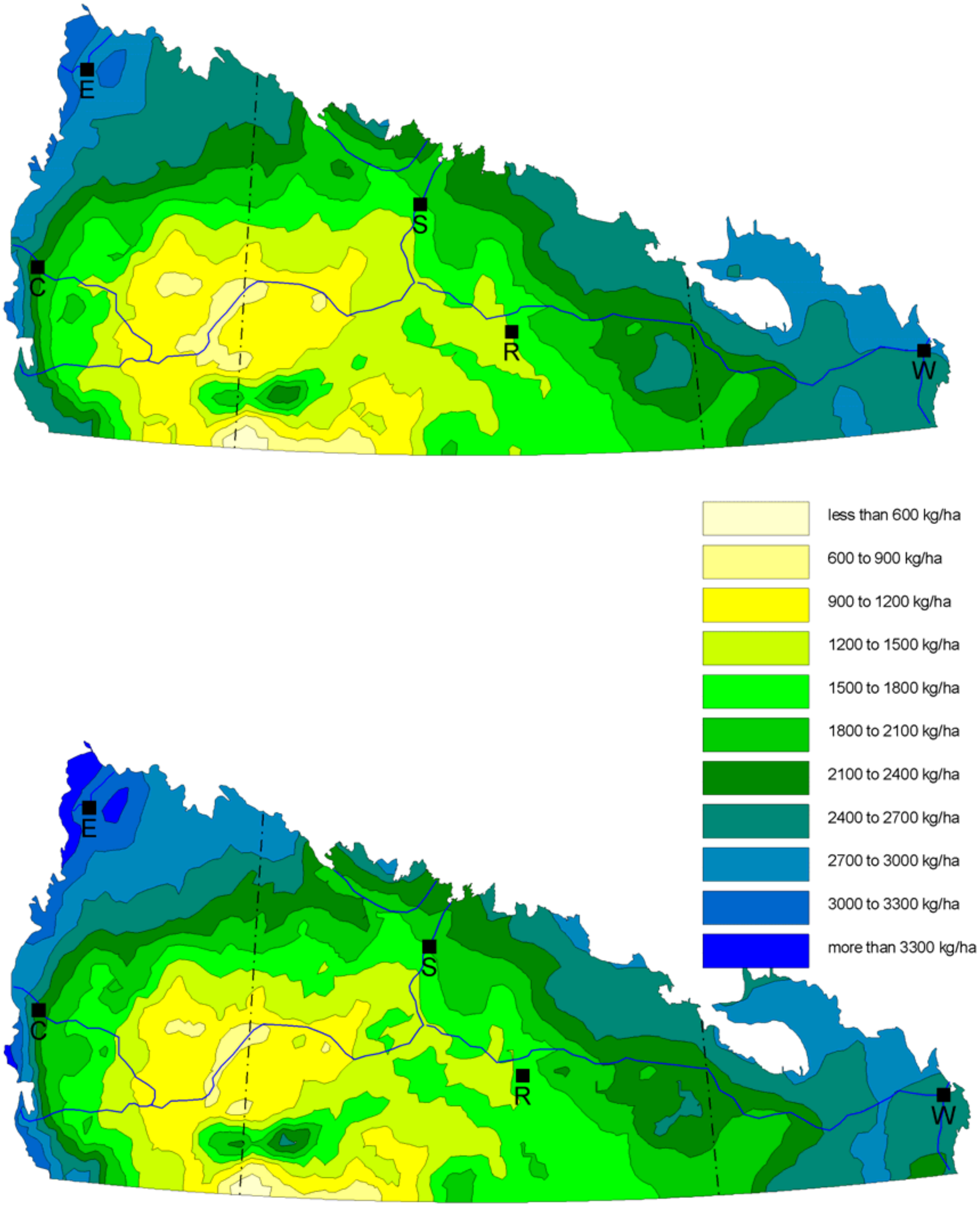

Figure 9. **Predicted production on loam in 1961-90 (top) and in the 2050s (CSIROMk2b B11 scenario) according to Model 1 (bottom).**

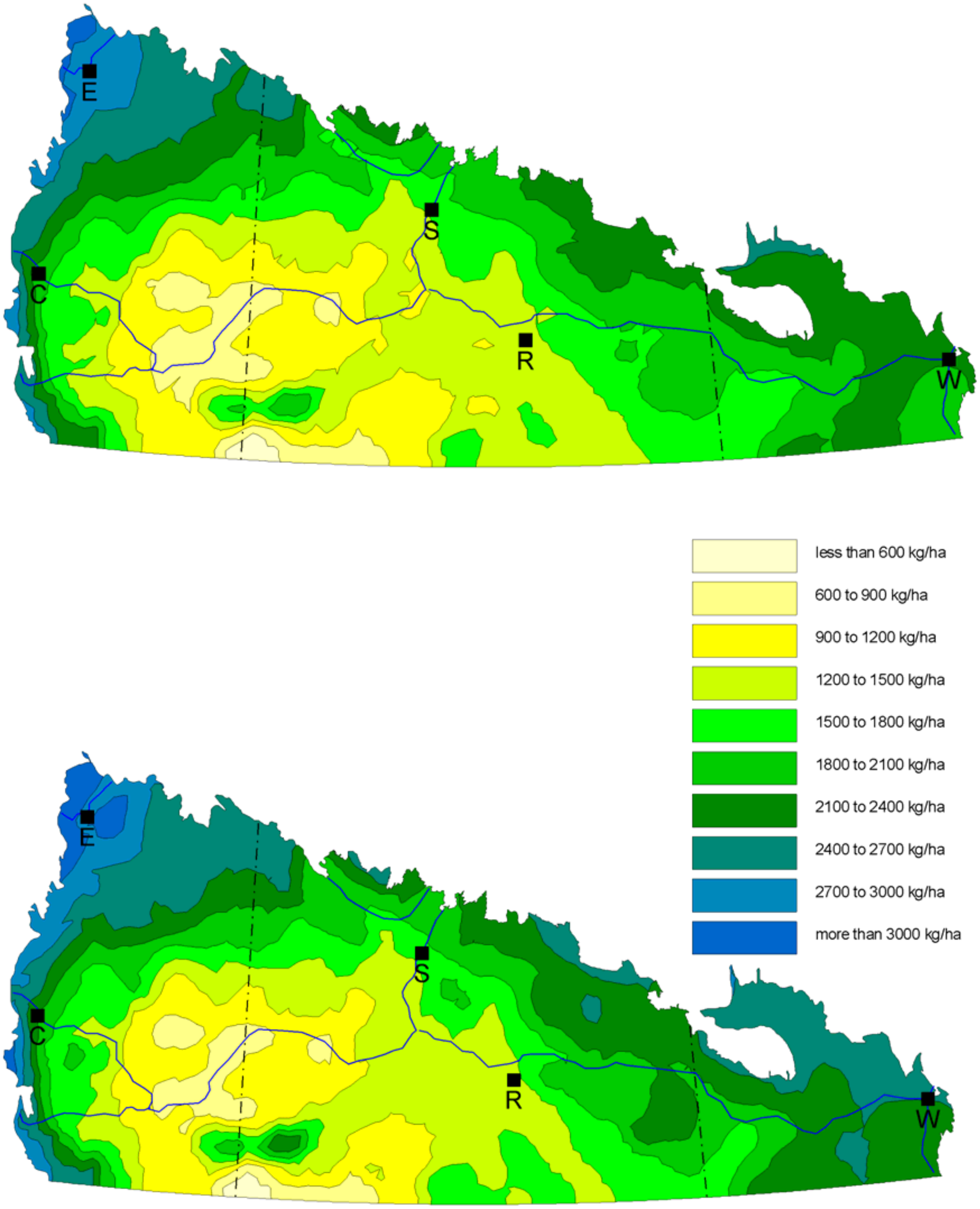

Figure 10. Predicted production on loam in the 2050s (CSIROMk2b B11 scenario), according to Model 2 (top) and Model 3 (bottom).

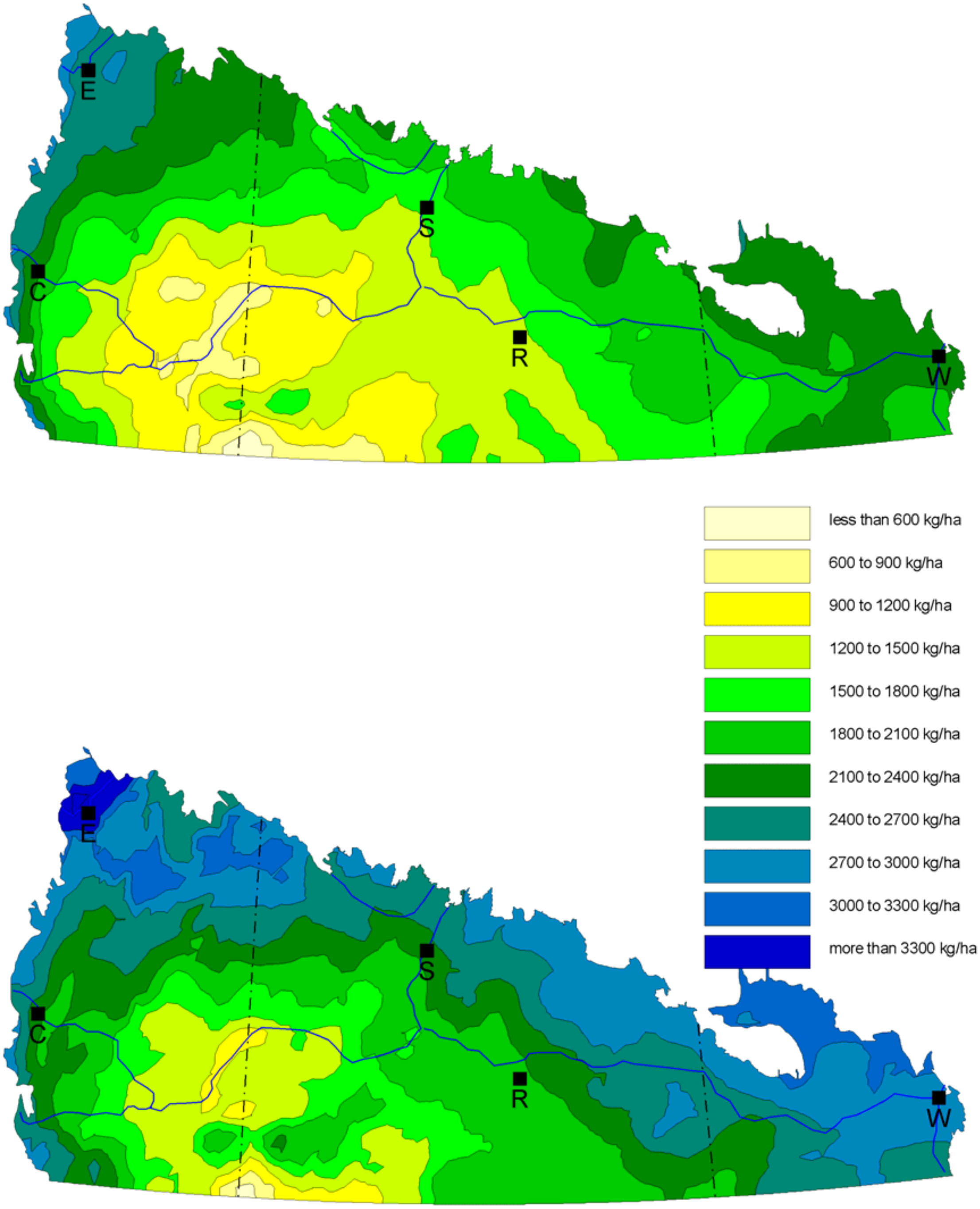

Figure 11. **Predicted production on sand in 1961-90 (top) and in the 2050s (CSIROMk2b B11 scenario) according to Model 1 (bottom).**

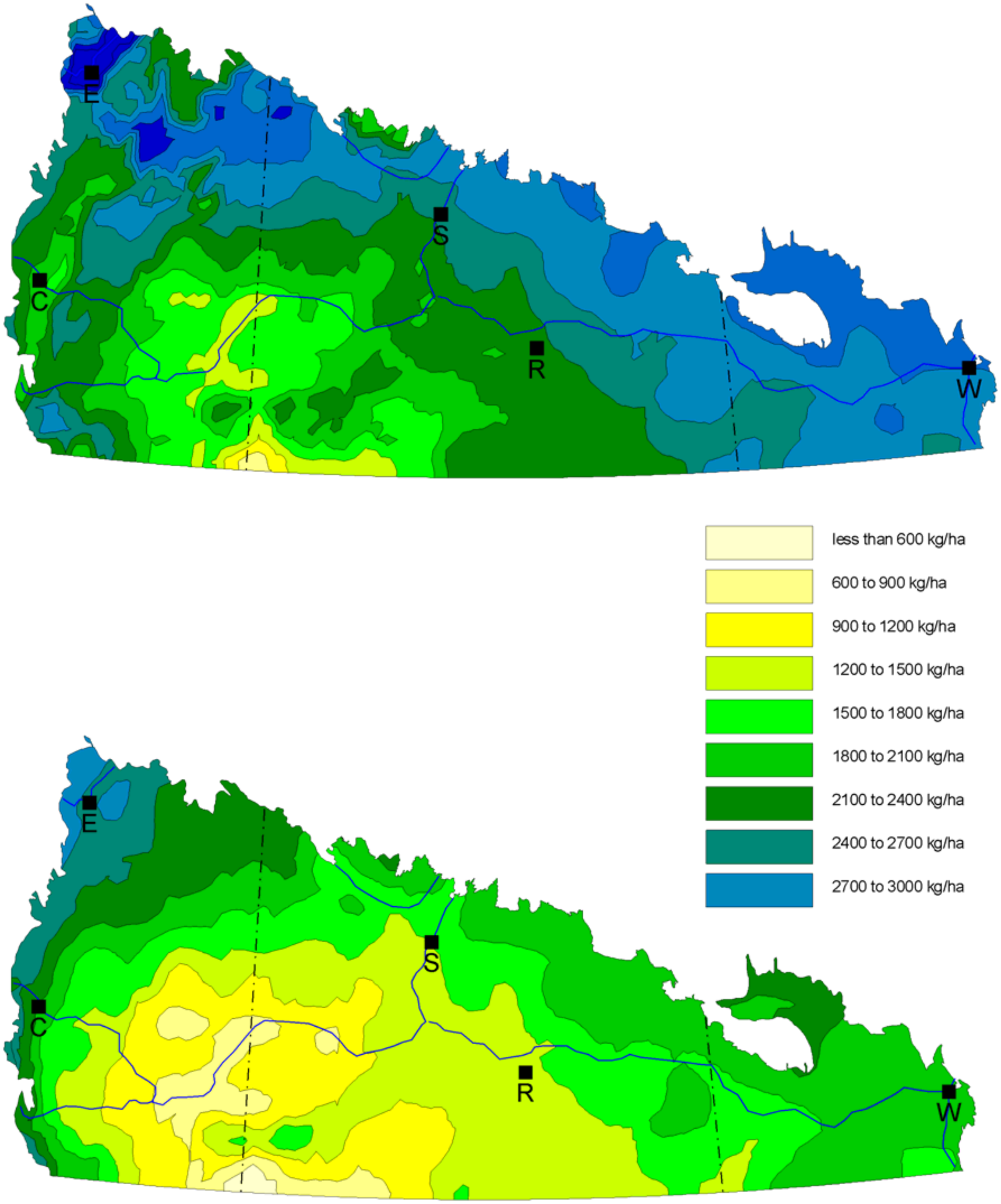

Figure 12. Predicted production on sand in the 2050s (CSIROMk2b B11 scenario), according to Model 2 (top) and Model 3 (bottom).

4. DISCUSSION

The approach of this study was to use regression models to explore the geographic patterns of climate and grassland production over the Canadian Prairies. This approach has proven useful in studies of the U.S. Great Plains, where models have been developed to relate climate variables to grassland production (Sims et al. 1978, Sala et al. 1988, Epstein et al. 1996, 1997a, 1997b, 1998, Paruelo et al. 1999), proportions of plant species (Epstein et al. 1998) or plant functional types (Epstein et al. 1997a, 2002b, Paruelo and Lauenroth 1996), and rates of decomposition (Epstein et al. 2002a).

In general, these models have used simple climatic variables such as annual precipitation and mean annual temperature. The current study expanded on this approach by using derived variables that relate to the mechanisms by which climate affects vegetation. For example, because vegetation response is more closely linked to temperatures in the growing season than in the dormant season, the sum of growing degree-days (i.e. daily deviations above a temperature threshold, usually 5° C) is widely used to represent the thermal environment for plant growth (Tuhkanen 1980). Similarly, vegetation response to moisture depends not so much on total precipitation as on the part that is used for evapotranspiration. Some previous studies have related evapotranspiration estimates from water balance models to vegetation geography (Stephenson 1990, Frank and Inouye 1994) and productivity (Rosenzweig 1968, Webb et al. 1978).

A long historic time-series from Manyberries, AB (Smoliak 1986), was analyzed to explore the application of water balance results to grassland productivity data. Water balance models require an estimate of potential evapotranspiration (PET), which is considered to be the amount of evapotranspiration that would occur if there were no limitations on moisture supply. While this concept originated with the Thornthwaite's (1948) method, more refined calculations of PET such as the Penman method have been developed (Jensen et al. 1990). However, the Penman method requires variables such as wind speed and humidity that are only available at a few climate stations. Two methods aimed at estimating Penman PET from simpler variables were tested: Jensen-Haise (Jensen et al. 1990) and Baier-Robertson (Baier and Robertson 1965, Baier 1971). The Jensen-Haise method is more data-demanding in that it requires global radiation, which is not available for most climate stations, although some studies have estimated it from regional maps (Hogg 1994). However, the Manyberries analysis showed that the less data-demanding Baier-Robertson method gave evapotranspiration results that were as closely related to production as those based on the Jensen-Haise method.

The best relationship for the year-to-year time-series at Manyberries showed production increasing with yearly actual evapotranspiration (AET). Water balance models calculate monthly AET as a function of monthly PET, which sets the upper limit, and soil moisture, which depends on the level from the previous month plus the current month's precipitation. In the dry climate of the prairie region, low soil moisture frequently limits AET to a level below that of PET. A significant regression was also obtained between production and annual water deficit (AET – PET, i.e. the amount by which the actual rate of evapotranspiration falls short of the potential rate), but the relationship was not as close as that with AET alone.

Annual AET proved a better predictor of production than annual precipitation in the Manyberries time series analysis. One advantage of using AET is that it does not include the precipitation that is lost to runoff or deep drainage, which does not contribute to plant production. Another advantage is that the water balance model accounts for the effect of fall rain and winter snowfall on the amount of moisture available for evapotranspiration in the following growing season. This effect is widely recognized in the region, and stocking rate plans for the coming year are based on these sources of moisture from the preceding year. Statistical relationships with AET were also found in other shorter time-series of production data. One limitation of the current analysis is that it did not distinguish transpiration from direct soil evaporation, both of which contribute to AET. Subtracting direct soil evaporation, which does not contribute to plant production, could improve relationships.

Geographic patterns of grassland production in the Canadian Prairies were analyzed by relating average production to average climate at study areas distributed across the region. In this case, the best relationship showed production increasing with annual water deficit (AET–PET) based on 1961-90 climatic normals. Note that AET-PET is a negative number, so the relationship implies that production is greater at higher or “less-negative” values of AET-PET, even though in common language we would refer to these as smaller water deficits. Maps of annual production predicted from the relationship with water deficit (Figure 3) related plausibly to our understanding of ecological patterns in the region.

A similar approach was used by Hogg (1994) to relate climate to the distribution of forest in the Prairie Provinces. His climatic moisture index (CMI) was calculated as annual precipitation minus potential evapotranspiration (PPT-PET), with PET estimated by the Jensen-Haise method. The boundary between forest and grassland matched a CMI value of zero. Hogg’s CMI differs from the water deficit used in the current analysis in that PPT is used rather than AET. AET is less than PPT by the amount of water surplus (runoff or deep drainage). The difference can be large in humid regions where PPT frequently exceeds the capacity for evapotranspiration (PET), resulting in significant runoff. However, in dry climates, AET is closer to PPT. In the current analysis, water surplus usually occurred only in March or April, when snowmelt plus current PPT exceeded PET. Water surplus was larger on sand (lower water-holding capacity) than on loam, because surplus only occurs after the water holding capacity is filled. Therefore, the model estimate of AET was somewhat lower on sand than on loam for a given climate. On loamy soils, annual water deficit (AET – PET) was fairly close to Hogg’s CMI (PPT – PET).

Lower values of AET and AET-PET imply that lower production is predicted on sand than on loam. This agrees with the lower grazing capacity assigned to sand sites in Alberta (Wroe et al. 1988) and Saskatchewan (Abouguendia 1990), and with the common perception that sands are dry sites. However, the “inverse texture hypothesis” suggests that, in dry climates, production is higher on coarser-textured than on finer-textured soils, while the opposite is true in humid climates. This hypothesis has been supported by analyses of geographic patterns of production in U.S. grasslands (Sala et al. 1988, Epstein et al. 1997b). The probable explanation is the greater role of direct soil evaporation in dry climates. In coarse-textured soils, rainwater drains quickly to lower soil layers where it is protected from direct soil evaporation, whereas in fine-textured soils it is held near the surface. The current analysis had too few data-points on each site type to test this hypothesis. If it were valid for the Canadian Prairies, it would not be captured by the modelling approach used here, with a single water-holding capacity for the entire soil profile, and a single value for evapotranspiration. Modelling to reflect this hypothesis would require transfers of water between shallower and deeper soil layers, and separation of direct evaporation from transpiration.

While current production patterns in the Canadian Prairies were well-represented by the relationship with water deficit, use of this relationship to predict changes under a warmer future climate would clearly be inappropriate, because of extrapolation beyond the range of the underlying data. To provide a basis for prediction, grasslands in the warmer climates of the U.S. Great Plains were taken as analogues for the future climate of the Canadian Prairies. The best models for the combined Canadian and U.S. dataset showed production increasing with either AET or PPT, and with dominance by warm-season (C_4) grasses. The best relationship incorporating a thermal variable showed production increasing with the ratio of actual to potential evapotranspiration (AET/PET) and with C_4 dominance.

The positive relationship between production and AET has been shown in other studies employing water balance models. Rosenzweig (1968) related net primary productivity to AET for a set of ecosystems from around the globe. Webb et al. (1978) did the same for the set of U.S. grassland sites studied under the International Biological Programme. The distribution of vegetation formations (shortgrass prairie, tallgrass prairie, deciduous forest, etc.) has been related to biplots of AET and water deficit, both globally (Frank and Inouye 1994) and for North America (Stephenson 1990). In these diagrams, the transition from shortgrass prairie (lower production) to tallgrass prairie (higher production) is related to both higher AET and smaller water deficits (i.e. higher values of AET-PET).

Similarly, U.S. studies have shown the increase in grassland production with annual precipitation (Sims et al. 1978, Sala et al. 1988, Epstein et al. 1996, 1998). In the U.S., both precipitation and grassland production show a simple westward decline across the Great Plains (Schimel et al. 1990). Where thermal effects have been examined, either by including both temperature and precipitation as independent regression variables (Sims et al. 1978), or by analyzing variation in temperature at a constant level of precipitation (Epstein et al. 1996, 1997b), yield has decreased with increasing temperature. This is presumably because of the effect of higher temperature in increasing potential evapotranspiration.

AET was clearly superior to PPT in predicting year-to-year variation in production at Manyberries. However, in the analysis of geographic patterns of production over Canadian and U.S. grasslands, AET lost its advantage, and PPT was about as well related to production. In the time-series analysis, the ability of the water balance model to carry forward moisture from the previous fall and winter clearly improved the relationship of AET with production. Years with unusually high fall precipitation led to higher production than would be expected from current rainfall, with the result that AET was a better predictor than PPT. However, the analysis of geographic patterns relied on average values of climatic variables, so the advantage of better representing unusual years was eliminated. In a region of dry climates, AET is primarily limited by the supply of water from PPT, and the geographic pattern of AET is mainly determined by the pattern of PPT. In more humid climates, AET is increasingly limited by the energy available for evaporation (i.e. by PET) (Stephenson 1990). AET may be a more robust predictor of productivity over a broader range of environments.

Analysis of the combined Canadian and U.S. data also showed that dominance by C_4 grasses was related to higher productivity. This is probably related to the higher water use efficiency of plants with the C_4 photosynthetic pathway, which implies that C_4s should have higher photosynthetic rates at a given level of moisture availability (Long and Hutchin 1991).

The probability of dominance by C_4s was found to increase with annual growing degree-days, and was higher on sand than on loam. The relationship with degree-days conforms with the current geographic pattern in which Canadian and northern U.S. grasslands are dominated by C_3s such as *Stipa* spp., *Agropyron* spp., and *Festuca* spp., while grasslands dominated by C_4s such as *Andropogon* spp., *Panicum* spp., and *Bouteloua* spp. become more common southward. The relationship with soil texture can be seen even in Canadian grasslands, where C_4 grasses including sand reed grass (*Calamovilfa longifolia*) and sand dropseed (*Sporobolus cryptandrus*) are much more common on sands than on finer-textured soils. Other studies have obtained similar results. Collatz et al. (1998) used a photosynthetic model to predict the shift from C_3 dominance to C_4 dominance in warmer climates. Epstein et al. (1997a) found that the percentage of C_4s in U.S. grasslands increases with mean annual temperature, as well as with higher precipitation and coarser-textured soils, while the percentage of C_3s shows the opposite trends. Epstein et al. (1998) extended this analysis to individual C_3 and C_4 species. Paruelo and Lauenroth (1996) found that the proportion of C_4s in North American grasslands increases with mean annual temperature, annual precipitation, and the proportion of precipitation falling in summer. Paruelo et al. (1998) found that these trends also applied in South American grasslands. Winslow et al. (2003) argued that the main effect of temperature is on the timing of the growing seasons for C_3s and C_4s, and modelled their proportions as a function of water availability during the growing season for each group.

Modelling the impacts of climate change on grassland productivity followed the approach of using multiple models and comparing their results. This approach recognizes that any model is an imperfect representation of reality, but assumes that greater confidence can be placed in results that are supported by several different models. Five climate change scenarios for the 2050s were selected to cover the range of predictions among the most recent GCM models. However, the results in terms of changes in production were relatively similar for all five climate change scenarios. Three models relating climate to grassland production were used. Two of these were developed in the analysis of the combined Canadian and U.S. data. Model 1 used AET, which is mainly controlled by the pattern of annual precipitation, whereas Model 2 used AET/PET, so is controlled by both precipitation changes and temperature changes. Both models used a second independent variable for C_4 dominance, which was predicted from the change in growing degree-days. A third model from the literature (Epstein et al. 1997a) was used to bring in a completely independent comparison.

On loam soils, Model 1 predicted no change or small increases in grassland production for the 2050s in the Canadian Prairies. When averaged over the region, these increases ranged from 0% to 7% among the five GCM scenarios. Models 2 and 3 generally predicted decreases, ranging from 8% to 17% for Model 2 and from 0% to 11% for Model 3. These differences can be related to the variables included in the model. Model 1, using AET, was mainly controlled by the small increase in annual precipitation predicted by most scenarios. Models 2 and 3 included thermal effects, in which rising temperature (implying higher PET) tends to reduce productivity. Note that the variable for C_4 dominance included in Models 1 and 2 had no effect on these results, because almost none of the Canadian Prairies was predicted to shift to C_4 dominance on loam soils. There is no obvious reason to consider one of these models the “correct” one.

The most striking thing about the results is that the predicted changes from all three models are relatively modest. The patterns of grassland productivity predicted for the Canadian Prairies in the 2050s are similar to current patterns (Figures 9 and 10), in spite of significant increases in temperature. That these modest changes are shown by different models using different variables, including some models that included the effect of temperature on production, provides reinforcement for this conclusion.

The conclusion that large decreases in productivity under climatic warming are unlikely receives support from several ecosystem simulation studies in U.S. grasslands using older GCM scenarios. Schimel et al. (1990) applied the CENTURY model to a site in central U.S., using the GISS scenario for CO_2 doubling. Both temperature and precipitation increased in this scenario. The model predicted an increase in net primary productivity, related to both the increase in precipitation and the increase in nitrogen availability with faster decomposition at warmer temperatures. Schimel et al. (1991) extended CENTURY simulations to the entire Great Plains using spatial data for climate and soil texture. This again showed an increase in net primary productivity for the northern plains, attributed to the increase in precipitation in the GISS scenario. Parton et al. (1996) and Ojima et al. (1996) applied CENTURY to grassland sites around the world, using the GFDL and CCC climate change scenarios, and obtained similar results to the Schimel studies for sites in Montana and Colorado. Similar results were obtained by Baker et al. (1993), who applied the SPUR model to U.S. rangelands, using the GISS, GFDL, and UKMO climate change scenarios. All of the simulations resulted in an increase in grassland production in the northern part of the Great Plains, except that the GFDL scenario showed a decrease in the eastern part of the northern plains (North and South Dakota). The three climate change scenarios showed a decrease in soil organic matter in the northern plains, related to faster decomposition at higher temperatures, and a decrease in the carbon:nitrogen ratio in soil.

On sand soils, Models 1 and 2 predicted significant increases in production, whereas Model 3 predicted small decreases. This resulted from the positive effect of C_4 dominance on production in the first two models, and the predicted shift to C_4 dominance on sand soils over most of the Canadian Prairies with rising temperatures. However, it must be acknowledged that the modelling of the C_4 effect in this analysis was limited by the available data, which only supported a binary variable for C_3 dominance versus C_4 dominance. Data for the actual percentages of C_3s and C_4s might have permitted more realistic modelling of the C_4 effect. Use of the binary variable might have exaggerated the change in production on sand soils. Conversely, it may have underestimated the change on loam soils, because an increase in the percentage of C_4s which did not reach the threshold for C_4 dominance could still contribute to higher productivity.

Other studies have addressed the effect of climate change on distribution of C_3s and C_4s. Long and Hutchin (1991) reviewed the physiological differences between C_3 and C_4 species, and concluded that because C_4s are more active at warmer temperatures, climatic warming would allow them to develop earlier in the spring, possibly resulting in a northward expansion of their distribution. Coffin and Lauenroth (1996) simulated grassland composition using STEPPE-GP and one of the older climate change scenarios, and found a shift from C_3 to C_4 dominance with climatic warming at northern U.S. sites (i.e. close to the Canadian Prairies). Epstein et al. (2002b) applied three of the older climate change scenarios to the models for C_3/C_4 distribution developed by Paruelo and Lauenroth (1996), and found significant increases in the proportion of C_4s for most North American grasslands, including the Canadian Prairies. They suggested that higher water use efficiency could lead to higher productivity and/or reduced transpiration. Contrasting results were obtained in northeastern Colorado by Alward et al. (1999), who related a recent decline in the dominant C_4 grass (*Bouteloua gracilis*) to rising temperatures, but this was over a short time span (<20 years).

The direct fertilization effect of rising CO_2 concentrations could complicate the shift to C_4s. Increasing CO_2 theoretically provides a greater relative benefit to C_3s than C_4s (Long and Hutchin 1991, Parton et al. 1994). However, ecosystem experiments have shown that, under the dry conditions typical of grasslands, this advantage tends to be eliminated (Nie et al., 1992; Campbell and Stafford Smith, 2000). Winslow et al. (2003) modelled the impacts of climate change on proportions of C_3s and C_4s on the basis of changes in water availability during the growing season for each group, and concluded that these changes may mask any benefit of rising CO_2 concentrations to C_3s.

The current analysis has only looked at C_3s and C_4s as groups, and has not considered individual species. If the proportion of C_4s in Canadian grasslands does increase, the implications could vary depending on the species involved. In the drier parts of the region on medium to fine-textured soils, the most abundant C_4 is *Bouteloua gracilis* (blue grama). Because this is a low-growing, mat-forming grass, any increase in its proportion over the accompanying C_3 midgrasses would be unlikely to increase production. However, other C_4s that could increase are mid- to tall grasses. *Schizachyrium scoparium* (little bluestem) is a mid-grass that is already widespread, but rarely dominant, across the region, especially on warm valley slopes. There are a number of C_4s in the tall-grass prairie that just makes it into Canada in southern Manitoba. The most abundant of these is *Andropogon gerardii* (big bluestem), a tall grass with scattered populations westward as far as southeastern Saskatchewan. On sands and dunesands, *Calamovilfa longifolia* (sand reed grass), a mid- to tall species, is one of the community dominants throughout the region, and *Sporobolus cryptandrus* (sand dropseed) can also be an abundant mid-grass. Further work on changes in grassland composition should take modelling to the level of individual species. In the U.S., Epstein et al. (1998) have shown distributions of individual grass species in relation to climatic and soil variables.

This analysis has considered only climatic effects on grassland production. Another factor that could affect production is the fertilizing effect of rising CO_2 concentrations. Parton et al. (1996) and Ojima et al. (1996) used an ecosystem model (CENTURY) to simulate the effect of doubling CO_2 concentrations on grassland sites around the world, and found increases in production. Similar results were obtained by Baker et al. (1993), who used the SPUR model to simulate CO_2 doubling without climate change in U.S. rangelands. Field experiments in grassland have shown increases in production ranging from 0 to 30% with doubling of ambient CO_2 concentrations (Campbell and Stafford Smith 2000). However, some research has shown a reduction in forage quality with CO_2 fertilization (Campbell and Stafford Smith 2000).

It should be emphasized that this geographic analysis deals with average levels of production. These are important, because they determine the long-term grazing capacities that are used in planning of grazing operations (Wroe et al. 1988, Abouguendia 1990). However, as the time-series analysis of the Manyberries data emphasizes, our grasslands show wide year-to-year variation in production related to weather. Any increase in the frequency or duration of drought as a result of climate change could have as important an impact on grazing operations as that of changes in average production levels. Future research should address the question of changes in drought occurrence and its impact on production and grazing capacity.

In conclusion, this study has not provided a definitive answer regarding changes in grassland production to be expected under climate change over the next fifty years. The answer depends on which impact model is used, and there is no obvious basis for choosing among them. However, for loam soils, all of the models indicated only modest changes in the pattern of production levels over the region. The CO_2 fertilization effect, which was not addressed in this study, could further moderate any tendency to decreasing productivity. This is by contrast with the predictions of "desertification", implying drastic reduction in production levels, that have been made in some assessments. This study has also shown that C_4 grasses will probably become more abundant in our northern grasslands under climatic warming, especially on coarse-textured soils, and that this could contribute to higher productivity in some circumstances.

5. STAKEHOLDER CONSULTATION

The main vehicle for stakeholder consultation was a workshop held at Saskatchewan Research Council in December of 2003. Unfortunately, the attendance was low, probably because of the preoccupation of many stakeholders at that time with the BSE issue and the closure of the U.S. border to beef exports. However, good discussion occurred among project scientists and managers of grazing on federal and provincial lands in Saskatchewan. Notes on this discussion are presented in Appendix 5, and are summarized below.

Native rangelands in Canada are a mixture of privately, provincially, and federally (PFRA) managed lands. Decisions on long-term stocking rates are made in a variety of ways, with government land managers using published grazing capacity information, which is based on average annual grassland production, and private producers relying more on personal experience. Monitoring of grassland production, to provide better information on which to base grazing capacities, also varies. Alberta has maintained an extensive network of range benchmark sites, with annual monitoring of yield. This activity is much more limited in Saskatchewan and Manitoba, with only PFRA maintaining a few benchmark sites. Government pasture managers also base grazing capacity decisions on long-term stocking records of fields with high or improving range condition.

All types of rangeland managers adjust stocking rates in individual years to cope with variation in weather and production. Monitoring of fall rain and winter snowfall is used to forecast production in the coming growing season, and stocking plans are adjusted on the basis of this information. The actual adjustment of stocking is done in a variety of ways. If lower than normal production is expected, government pastures can start the grazing season later or end it earlier, reduce the number of animals accepted from each patron, or not fill vacancies among patrons. However, if higher than normal production is expected, government pastures generally do not increase stocking as much as they could, because of a priority on conservation.

Private producers have a wide range of adaptations for drought years, of which the most commonly used is heavier than normal culling of the herd. Other adaptations include using feeders as part of the herd and selling them in dry years, renting alternative grazing lands, keeping a portion of their own land as a reserve for dry years, sowing annual forage on cropland or grazing failed annual crops, and building up a stockpile of feed. Producers in the drier regions of the Prairies where drought is more frequent are more likely to have emergency plans in place.

The results of the climate change modelling described above were presented to the stakeholders. Because this research did not indicate a drastic reduction in grassland production, the implications for the long-term future of grazing operations were not as negative as originally feared. The longer grazing season (and therefore shorter feeding season) in a warmer climate would be an advantage to producers, but there could be more need to maintain litter cover against direct soil evaporation, more heat stress on animals, and new disease problems. Any negative impacts of climate change on water supply in wells or dugouts would have an important impact on grazing operations. Adaptations to future climate change could including seeding of warm-season grasses and new water development. Stakeholders emphasized the need for monitoring to detect long-term changes in grassland productivity related to climate change. Information from such monitoring would be required to initiate changes in grazing capacity ratings.

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APPENDIX 1
Study areas used for grassland production data in Canada

study area		climate stations	latitude (°)	longitude (°)	elevation (m)	measurement years	source
Antelope Creek, Grazed	AB	Brooks AHRC	50.59	112.17	777	1988, 89, 90, 96, 97, 98, 99, 2000	Alberta Public Lands 2001
Antelope Creek, Ungrazed	AB	Brooks AHRC	50.59	112.17	777	1988, 89, 90, 96, 97, 98, 99, 2000	Alberta Public Lands 2001
Antelope Lake	AB	Coronation A	51.65	111.30	762	1976 - 1978	Smoliak et al. 1979
Berry Creek	AB	Pollockville	51.13	111.47	732	1972 - 1978	Smoliak et al. 1979
Big Stone	AB	Pollockville	51.23	111.18	793	1972 - 1978	Smoliak et al. 1979
Big Valley North	AB	Craigmyle	51.92	112.62	854	1969 - 1978	Smoliak et al. 1979
Big Valley South	AB	Craigmyle	51.92	112.62	854	1969 - 1978	Smoliak et al. 1979
Border Coop	AB	Manyberries CDA	49.00	110.08	854	1976 - 1978	Smoliak et al. 1979
Claresholm	AB	Claresholm Waterworks	50.02	113.73	1052	1971 - 1978	Smoliak et al. 1979
Cypress Hills	AB	Klintonel	49.58	110.10	1402	1976 - 1978	Smoliak et al. 1979
Parkland - Dvr	AB	Brownfield	52.45	111.22	756	1992 - 2000	unpub. data from H. Loonen
Parkland - Mtl	AB	Brownfield	52.37	110.94	735	1989 - 2000	unpub. data from H. Loonen
Parkland - Rbt	AB	Brownfield	52.32	110.92	680	1989 - 2000	unpub. data from H. Loonen
Parkland - Hwe	AB	Brownfield	52.48	110.72	694	1989 - 2000	unpub. data from H. Loonen
Parkland - Kch	AB	Brownfield	52.49	110.63	681	1992 - 2000	unpub. data from H. Loonen
Parkland - Kpg	AB	Brownfield	52.47	110.54	706	1989 - 2000	unpub. data from H. Loonen
Parkland - Mlr	AB	Brownfield	52.31	110.69	684	1989 - 2000	unpub. data from H. Loonen
Parkland - Vty	AB	Coronation A, Scotstown, Sibbald, Kerrobert	52.09	110.17	727	1989 - 2000	unpub. data from H. Loonen
Little Fish Lake	AB	Craigmyle	51.42	112.23	976	1972 - 1978	Smoliak et al. 1979
Loyalist	AB	Coronation A	51.90	110.93	762	1972 - 1978	Smoliak et al. 1979
Manyberries, Grazed	AB	Manyberries CDA	49.12	110.47	934	1951 - 1989	Smoliak 1986 and unpub. data from W. Willms
Manyberries, Ungrazed	AB	Manyberries CDA	49.12	110.47	934	1969 - 1978	Smoliak et al. 1979
Milk River Ridge	AB	Cardston	49.12	112.82	1280	1969 - 1978	Smoliak et al. 1979
Misty Lake	AB	Coronation A, Sibbald	51.77	110.55	808	1972 - 1978	Smoliak et al. 1979
Neutral Hills	AB	Coronation A	52.13	110.83	762	1972 - 1978	Smoliak et al. 1979
Pinhorn	AB	Manyberries CDA	49.13	110.78	915	1969 - 1978	Smoliak et al. 1979
Schuler	AB	Medicine Hat A	50.43	110.23	823	1976 - 1978	Smoliak et al. 1979
Spencer	AB	Coronation A	52.00	110.93	793	1972 - 1978	Smoliak et al. 1979
Stavely	AB	Pekisko	50.20	113.90	1372	1969 - 1978	Smoliak et al. 1979

study area		climate stations	latitude (°)	longitude (°)	elevation (m)	measurement years	source
Sunnynook	AB	Pollockville	51.32	111.68	777	1972 - 1978	Smoliak et al. 1979
Twin River	AB	Cardston	49.02	112.35	1250	1971 - 1978	Smoliak et al. 1979
Veteran	AB	Coronation A	51.97	111.10	793	1972 - 1978	Smoliak et al. 1979
Willow Creek	AB	Claresholm Waterworks	50.12	113.78	1052	1971 - 1978	Smoliak et al. 1979
Antler Upland	SK	Virden, Maryfield	49.67	101.42	549	1991 - 1993	unpub. Sask. Benchmark site
Arena	SK	Eastend 2, Claydon	49.37	109.08	1000	1991 - 1993	unpub. Sask. Benchmark site
Dundurn Sand Hills	SK	Saskatoon A	51.95	106.72	500	1996 - 1997	Houston 2000; shrub yield estimated
Great Sand Hills	SK	Ingebright Lake	50.36	109.13	725	1995	Thorpe and Godwin 1997; shrub yield estimated
Hatherleigh 1	SK	North Battleford A	53.07	108.02	640	1990 - 1993	unpub. Sask. Benchmark site
Hatherleigh 2	SK	North Battleford A	53.10	107.97	671	1991 - 1992	unpub. Sask. Benchmark site
Kindersley-Elma	SK	Kindersley A	51.48	109.33	671	1992 - 2000	unpub. Sask. Benchmark site
Lake Alma	SK	Weyburn	49.15	104.20	720	1993 - 1997	unpub. Sask. Benchmark site
Laurier	SK	Weyburn	49.48	104.05	620	1994 - 2000	unpub. Sask. Benchmark site
Mainprize	SK	Weyburn	49.32	103.52	549	1991 - 1992	unpub. Sask. Benchmark site
Manito	SK	Scott CDA; Scotstown, Paradise Valley for PPT	52.63	109.78	640	1993	unpub. Sask. Benchmark site
Matador	SK	Swift Current CDA	50.70	107.72	686	1968 - 1972	Coupland 1973
McCraney	SK	Watrous	51.37	105.88	595	1992, 93, 96, 97, 98, 99	unpub. Sask. Benchmark site
Millie	SK	Ingebright Lake	50.38	109.03	740	1992 - 1993	unpub. Sask. Benchmark site
Monet	SK	Beechy	51.08	108.02	671	1992 - 2000	unpub. Sask. Benchmark site
Tompkins	SK	Ingebright Lake	50.25	109.15	740	1992 - 1993	unpub. Sask. Benchmark site
Valjean	SK	Eastleigh	50.38	106.15	625	1991 - 1997	unpub. Sask. Benchmark site
Vonda	SK	Saskatoon A	52.32	106.10	534	1994 - 1996	unpub. Sask. Benchmark site
Ellice-Archie	MB	Rocanville	50.38	101.28	460	1994 - 1996	unpub. Sask. Benchmark site

APPENDIX 2
Environmental characteristics of Canadian study areas

study area	range site	texture	water-holding capacity (mm)*	dominant species**			grazing***
				#1	#2	#3	
Antelope Creek, Grazed	burnout	clay loam to loam	175	Stip com	Carx spp	Bout gra	MG
Antelope Creek, Ungrazed	burnout	clay loam to loam	175	Stip com	Carx spp	Bout gra	HG? to 1987 then UG
Antelope Lake	dunesand	sand	50	Rosa spp	Symp occ	Arte fri	UG - LG
Berry Creek	burnout	sandy loam	100	Stip com	Agro smi		UG - LG
Big Stone	loamy	loam	150	Stip com	Stip cur		UG - LG
Big Valley North	sandy	light loam	100	Fest sca	Carx spp		UG - LG
Big Valley South	loamy	loam	150	Stip cur	Bout gra	Carx spp	UG - LG
Border Coop	sandy	sandy loam	100	Stip com	Bout gra		UG - LG
Claresholm	limey	sandy loam	100	Stip cur	Fest sca	Stip com	UG - LG
Cypress Hills	gravelly	silty loam	150	Fest sca	Stip cur		UG - LG
Parkland - Dvr	loamy	loam	150	Fest hal	Carx spp	Agro smi	LG to 1991 then UG
Parkland - Mtl	loamy	loam	150	Fest hal	Carx spp	Stip cur	LG to 1991 then UG
Parkland - Rbt	burnout	clay	250	Agro smi	Poa spp		UG for long time
Parkland - Hwe	sand	loamy sand	50	Fest hal	Juni hor	Carx spp	LG to 1991 then UG
Parkland - Kch	sand	loamy sand	50	Carx spp	Stip cur	Fest hal	UG for long time
Parkland - Kpg	sand	loamy sand	50	Fest hal	Carx spp	Rosa ark	UG - LG
Parkland - Mlr	dunesand	sand	50	Juni hor	Carx spp	Rosa ark	MG to 1983 then UG
Parkland - Vty	loamy	loam	150	Fest hal	Carx spp		LG to 1991 then UG
Little Fish Lake	loamy	silty loam	150	Fest sca	Carx spp		UG - LG
Loyalist	loamy	loam	150	Fest sca	Stip cur		UG - LG
Manyberries, Grazed	loamy	clay loam	200	Bout gra	Stip com	Carx spp	MG
Manyberries, Ungrazed	loamy	clay loam	200	Stip com	Agro smi	Carx spp	UG since 1926
Milk River Ridge	sandy	sandy loam	100	Fest sca	Fest ida	Carx spp	UG - LG
Misty Lake	loamy	loam	150	Fest sca	Stip cur		UG - LG
Neutral Hills	sandy	sandy loam	100	Fest sca	Stip cur		UG - LG
Pinhorn	loamy	loam	150	Stip com	Agro spp	Koel cri	UG - LG
Schuler	loamy	clay loam	200	Stip com	Bout gra	Agro spp	UG - LG
Spencer	loamy	clay loam	200	Fest sca	Stip cur		UG - LG
Stavely	loamy	silty loam	150	Fest sca	Dant par		UG since 1949
Sunnynook	burnout	sandy loam	100	Stip com	Agro smi		UG - LG
Twin River	loamy	silty loam	150	Fest sca	Fest ida	Agro spp	UG - LG

study area	**range site**	**texture**	**water-holding capacity (mm)***	**dominant species****			**grazing*****
				#1	**#2**	**#3**	
Veteran	loamy	clay loam	200	Fest sca	Stip cur		UG - LG
Willow Creek	gravelly	silty loam	150	Fest sca	Stip cur		UG - LG
Antler Upland	loamy	loam	150				UG (how long?)
Arena	loamy	clay loam	200	Stip cur	Carx spp	Agro smi	UG (how long?)
Dundurn Sand Hills	dunesand	sand	50	Carx spp	Stip com	Arte fri	mixture of MG & UG
Great Sand Hills	dunesand/sand	sand	50	Stip com	forbs	Cala lon	MG
Hatherleigh 1	loamy	loam	150				UG (how long?)
Hatherleigh 2	loamy	loam	150				UG (how long?)
Kindersley-Elma	saline upland	clay	250	Carx spp	Agro das	Agro alb	UG (how long?)
Lake Alma	loamy	clay loam	200				UG (how long?)
Laurier	loamy	clay loam	200				UG (how long?)
Mainprize	loamy	loam	150	Stip com	Agro spp	Stip vir	UG (how long?)
Manito	dunesand	sand	50				UG (how long?)
Matador	clayey	heavy clay	250	Agro das	Agro smi	Carx ele	LG to 1967, then UG
McCraney	sandy	sandy loam	100				UG (how long?)
Millie	sand	sand	50				UG (how long?)
Monet	loamy	clay loam	200				UG (how long?)
Tompkins	loamy	silty loam	150				UG (how long?)
Valjean	loamy	loam	150	Agro das	Stip cur	Carx spp	UG for long time
Vonda	loamy	loam or clay loam	175				UG (how long?)
Ellice-Archie	sandy	sandy loam	100				UG (how long?)

* Water-holding capacity in top 120 cm of soil, inferred from soil texture following De Jong and Shields (1988).

**Plant species:

Agro alb	Agropyron albicans
Agro das	Agropyron dasystachyum
Agro smi	Agropyron smithii
Arte fri	Artemisia frigida
Bout gra	Bouteloua gracilis
Cala lon	Calamovilfa longifolia
Carx ele	Carex eleocharis
Dant par	Danthonia parryi
Fest hal	Festuca hallii
Fest ida	Festuca idahoensis
Fest sca	Festuca scabrella
Juni hor	Juniperus horizontalis
Koel cri	Koeleria cristata
Poa spp	Poa spp.
Rosa ark	Rosa arkansana
Stip com	Stipa comata
Stip cur	Stipa curtiseta
Stip vir	Stipa viridula
Symp occ	Symphoricarpos occidentalis

***UG ungrazed, LG lightly grazed, MG moderately grazed, HG heavily grazed

APPENDIX 3
Climate and production data for Canadian study areas

	NEAREST MCKENNEY GRIDPOINT				NEAREST CLIMATE STATION											
	1961-90 NORMALS				1961-90 NORMALS			MEASUREMENT YEARS			ANNUAL PRODUCTION (kg/ha)					
study area	GDD	PPT (mm)	PET (mm)	AET (mm)	PPT (mm)	PET (mm)	AET (mm)	PPT (mm)	PET (mm)	AET (mm)	grass	forb	grass + forb	shrub	forb + shrub	total
Antelope Creek, Grazed	1626	351	700	351	342	697	342	272	735	272	801	72				872
Antelope Creek, Ungrazed	1626	351	700	351	342	697	342	272	735	272	642	52				694
Antelope Lake	1448	314	665	314	387	593	357	359	633	359	664				288	952
Berry Creek	1620	311	720	311	322	748	322	325	737	325	610				112	722
Big Stone	1534	309	688	309	322	748	322	325	737	325	1472				62	1534
Big Valley North	1410	414	606	414	394	649	394	401	633	401	2623	53		34		2710
Big Valley South	1410	414	606	414	394	649	394	401	633	401	1854	203		7		2064
Border Coop	1646	310	777	310	351	698	351	369	698	369	750	164		17		932
Claresholm	1429	433	666	429	428	659	426	480	635	440	976	229		292		1497
Cypress Hills	1299	422	629	421	450	652	450	483	641	457	1269	261		236		1766
Parkland - Dvr	1342	449	582	449	465	597	465	496	609	496	3061	310		0		3370
Parkland - Mtl	1411	398	606	398	465	597	465	499	616	499	2137	257		0		2394
Parkland - Rbt	1411	398	606	398	465	597	464	499	616	499	1678	56		0		1734
Parkland - Hwe	1403	405	590	368	465	597	396	499	616	419	855	171		1251		2278
Parkland - Kch	1403	405	590	368	465	597	396	496	609	415	1652	29		0		1682
Parkland - Kpg	1408	401	588	366	465	597	396	499	616	419	1378	188		421		1987
Parkland - Mlr	1445	382	610	362	465	597	396	499	616	419	438	266		2810		3514
Parkland - Vty	1426	374	607	374	355	593	355	348	643	348	2384	136		0		2520
Little Fish Lake	1444	394	641	394	394	649	394	398	615	398	2273				86	2359
Loyalist	1406	355	626	355	387	593	387	419	566	419	2124				239	2363
Manyberries, Grazed	1656	341	753	341	351	698	351	353	691	353						428
Manyberries, Ungrazed	1656	341	753	341	351	698	351	353	691	353	630	130		56		816
Milk River Ridge	1329	496	606	433	547	647	476	628	688	478	2106	319		16		2441
Misty Lake	1429	354	625	354	352	593	352	366	566	366	1751				99	1850
Neutral Hills	1422	383	610	382	387	593	387	419	566	408	1911				86	1997
Pinhorn	1749	351	741	351	351	698	351	353	691	353	940	106		8		1054

	NEAREST MCKENNEY GRIDPOINT				NEAREST CLIMATE STATION											
	1961-90 NORMALS				1961-90 NORMALS			MEASUREMENT YEARS			ANNUAL PRODUCTION (kg/ha)					
study area	**GDD**	**PPT (mm)**	**PET (mm)**	**AET (mm)**	**PPT (mm)**	**PET (mm)**	**AET (mm)**	**PPT (mm)**	**PET (mm)**	**AET (mm)**	**grass**	**forb**	**grass + forb**	**shrub**	**forb + shrub**	**total**
Schuler	1671	335	699	335	323	723	323	355	728	355	763	43		0		806
Spencer	1361	385	604	385	387	593	387	419	566	419	1934				84	2018
Stavely	1155	454	612	454	683	569	535	723	565	537	2498	258		113		2869
Sunnynook	1506	329	688	329	322	748	322	325	737	325	871				200	1071
Twin River	1542	426	655	426	547	647	520	644	694	537	1398	224		26		1648
Veteran	1401	354	633	354	387	593	387	419	566	419	2209				114	2323
Willow Creek	1406	420	665	420	428	659	428	480	635	480	1495	146		5		1646
Antler Upland	1620	463	636	463	463	633	463	500	557	484	1514	137		33		1684
Arena	1471	380	696	380	380	696	380	427	668	427	689	55		23		767
Dundurn Sand Hills	1634	349	625	327	347	612	326	380	605	349			1000	100		1100
Great Sand Hills	1694	348	719	338	322	744	322	450	695	397	1117	302		100		1519
Hatherleigh 1	1290	394	565	394	368	567	368	356	590	356	1628	97		0		1725
Hatherleigh 2	1217	420	543	420	368	567	368	336	599	336	1002	404		0		1406
Kindersley-Elma	1582	327	669	327	324	649	324	333	632	333	1416	132		22		1570
Lake Alma	1694	423	688	423	393	665	393	442	661	442	748	159		12		917
Laurier	1706	405	700	405	393	665	393	470	660	470	1038	282		0		1320
Mainprize	1771	403	701	403	393	667	393	459	644	459	2042	194		0		2236
Manito	1459	400	581	365	386	581	344	387	512	349	668	100		0		768
Matador	1657	328	679	328	330	611	330	303	604	303	1191	119		0		1310
McCraney	1531	375	614	375	395	613	395	489	586	480	1218	148		0		1365
Millie	1688	350	714	339	322	744	322	316	709	306	584	118		70		772
Monet	1687	310	694	310	327	663	327	381	661	381	1257	154		0		1404
Tompkins	1710	353	723	353	322	744	322	316	709	316	920	20		74		1014
Valjean	1663	355	681	355	380	651	380	419	626	419	1359	154		29		1440
Vonda	1534	379	585	379	347	612	347	396	605	396	1727	193		7		1928
Ellice-Archie	1592	445	612	427	409	614	409	528	572	437	1359	689		1		2049

APPENDIX 4
Study areas used for grassland production data in the United States

state	Major Land Resource Area	precip. zone (inches)	climate stations	climate (1961-90 normals) and water balance data					annual production (kg/ha)	
				GDD	PPT (mm)	PET (mm)	AET, loamy (mm)	AET, sand (mm)	sand	loamy
Colorado	67B		Greeley, Fort Morgan, Flagler, Springfield	2566	367	1112	367	367	2074	1457
Colorado/ Nebraska/ Kansas	72XA		Colby, Wray, Imperial, Julesburg	2658	461	1078	461	461	2354	2018
Montana	58A, 60B	14	Billings, Miles City, Circle, Glendive, Flatwillow, Denton	2095	356	867	356	348	2690	2466
Montana	58A, 60B	13		2095	330	867	330	328	2354	2018
Montana	58A, 60B	12		2095	305	867	305	305	2018	1569
Montana	58A, 60B	11		2095	279	867	279	279	1457	1345
Montana	58A, 60B	10		2095	254	867	254	254	1009	1177
North Dakota	53		Crosby, Stanley, Steele	1869	422	776	422	422		2354
North Dakota/ Montana/ S.Dakota	54		Beulah, Dickinson, Carson	1905	425	800	425	425	2242	2690
Nebraska	75, 102B, 106	25-34	West Point, Lincoln, Geneva	2882	733	885	733	670	3643	4064
Nebraska	65	14-17	Alliance, Ellsworth, Oshkosh	2257	430	970	430	429	2130	
Nebraska	65	17-22	Merriman, Hyannis, Arthur, Brownlee	2257	474	951	474	474	2578	
Nebraska	65	22-25	Brewster, Chambers	2435	568	920	568	539	2915	
South Dakota	Eastern		Sisseton, Watertown, Brookings, Sioux Falls	2259	572	775	571	529	3643	3587
South Dakota	West Central		Bison, Dupree, Murdo, Harrington	2280	440	889	440	440	2690	2298
Wyoming	34	10-14	Rawlins, Kemmerer	1433	257	817	257	257	1569	1233
Wyoming	34	7-9	Farson, Bitter Creek, Lost Cabin	1513	198	950	198	198	561	561
Wyoming	58A, 58B, 60A	15-17	Clearmont, Gillette, Kaycee, Douglas, Midwest, Buffalo	1934	355	941	355	355	2578	2130

APPENDIX 5
Summary of "Climate Change and Native Grasslands" Workshop held at Saskatchewan Research Council, December 5, 2003

ATTENDEES

Jeff Thorpe, Saskatchewan Research Council, Saskatoon
Bob Godwin, Saskatchewan Research Council, Saskatoon
Steven Wolfe, Geological Survey of Canada, Ottawa
Bill Houston, PFRA, Regina
Don Fontaine, Saskatchewan Agriculture, Saskatoon
Galen Loy, Saskatchewan Agriculture, North Battleford

WORKSHOP OBJECTIVES

- What will be the effects of climate change on grazing capacity of native grasslands in the Canadian Prairies?
- How will these changes affect grazing operations?
- How can the grazing industry adapt to climate change?

GROUP DISCUSSION: How is climate and production information used in planning grazing operations?

1. Do you use grazing capacity information to plan long-term stocking rates? Where do you get this information?

- **PFRA**
  - PFRA has used grazing capacity information for the past 15 years to plan long-term stocking rates.
  - PFRA is developing range management plans for its 87 pastures. This includes range condition surveys as a basis for determining whether stocking rates of individual fields are appropriate. Range condition assessments will be completed in 2004 for all PFRA pastures.
  - Published range condition and stocking rate guides for Alberta[1] and Saskatchewan[2] are used as the primary source of information. In Manitoba, there is no guide, so PFRA uses the Saskatchewan guide, and also refers to information from North Dakota and Minnesota.
  - PFRA also uses their own records of long-term stocking in fields that are in stable or improving range condition. This is considered to a good indication of the long-term grazing capacity, and is used to adjust the rates given in the published guides.
  - PFRA's experience is that the stocking rates given in the Saskatchewan guide are appropriate in the Brown and Dark Brown Soil Zones, but tend to be too low in the Black Soil Zone. There, PFRA increases the rates based on long-term stocking data.
  - Update of the published guides to include this information would be useful.

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[1] Wroe, R.A., S. Smoliak, B.W. Adams, W.D. Willms, and M.L. Anderson. 1988. Guide to range condition and stocking rates for Alberta grasslands. Alberta Forest, Lands and Wildlife.

[2] Abouguendia, Z.M. 1990. A practical guide to planning for management and improvement of Saskatchewan rangeland. New Pasture and Grazing Technologies Project, Regina.

- **Saskatchewan Provincial Pastures**
  - Saskatchewan is developing inventories and range management plans for its community pastures. At present, plans are completed for 17 of the 56 pastures.
  - Stocking rates are set using the tables in the Saskatchewan guide.
  - Long-term stocking records are also collected by pasture managers. However, this recording is not always consistent among pasture managers, and some records have been lost. Past records have not been entered into databases, and only exist as paper copies. Electronic forms were instituted this year. Collection of stocking records by pasture managers should be valuable, because they have no incentive to fudge the numbers.
  - Pasture managers are gathering precipitation information as well

- **Saskatchewan Co-op Pastures**
  - Lands Agrologists have done inventory and planning for a few of the 134 Co-op Pastures in Saskatchewan (approximately one per year).
  - Most planning is done by agreement among the patrons of the pastures.
  - Management varies from good to bad.
  - There is a lot of room for education in the Co-op Pasture system.

- **Saskatchewan Crown Grazing Leases**
  - About 8 million acres of Crown Grazing Leases, most of them with private producers on 33-year leases. 473,000 acres are leased to PFRA for their community pastures.
  - Lands Branch uses the Saskatchewan stocking rate guide to set the official number of AUMs on each lease for billing purposes. However, some rates were set a long time ago and probably have not been changed. Stocking rates used for billing are available to producers as information, but may not directly determine the stocking rates that they apply.
  - Anecdotally, actual stocking is often close to the official rate used for billing.
  - Lands Branch has only nine agrologists to supervise a large area of leases, so cannot check leases every year.
  - A range health monitoring system has been used for random audits for the last four years. Often these audits are done at the time a lease changes hands.
  - If Lands Branch finds out that a lease is badly overgrazed, there is a lengthy process by which the lease may eventually be taken away from the producer. This has happened on some occasions.
  - Probably more than 80% of the acreage is in large leases (2 sections or more). Leases tend to be larger in the Brown Soil Zone and smaller in moister regions. Generally, large leases are managed better than small leases.
  - Planning methods used by private producers (both on Crown Leases and on deeded land) vary widely.
  - Some private producers have good stocking records and make use of the Saskatchewan stocking rate guide. Over the last 15 years, there has been a lot of extension work on range management techniques, and many producers have been exposed to this information. Also forage clubs are being set up through the province.
  - But most stocking rate decisions are based on the experience and “gut feeling” of the producer with the number of animals that a given field will support. This is

particularly true for the large ranchers, many of whom have years of experience with their ranches, as well as knowledge passed down from previous generations.

- **Private land**
  - Privately owned rangeland could account for approximately 20% of the total rangeland in Saskatchewan.
  - Planning methods are the same as used by private producers on Crown Leases.

2. Do you monitor changes in forage production?

- **PFRA**
  - PFRA is monitoring three benchmark sites (fenced, ungrazed areas of about an acre) at Kindersley-Elma, Monet, and Laurier Pastures. Yield is measured every year, and species composition approximately every five years. These sites have been monitored for over 10 years.
  - Yield has been increasing in these sites since they were fenced, because of litter accumulation. It would be desirable to also monitor yield in grazed areas (using temporary cages), as is being done in Alberta.

- **Province of Saskatchewan**
  - Provincial staff are doing very little monitoring of forage yield.
  - Several benchmark sites were established on Provincial land in the early 1990s, but the monitoring program was not kept up.
  - A few individuals in Saskatchewan Agriculture may be doing some yield monitoring.
  - There could be producers who monitor yield, but it is not common.

3. Do you use monitoring results to adjust long term stocking rates?

- Monitoring of forage yield (e.g. in benchmark sites) has not yet been used to adjust long-term stocking rates.
- PFRA uses their records of actual stocking from fields that have been maintained in good condition to adjust long-term stocking rates.
- In both PFRA and Saskatchewan Provincial Pastures, stocking rates for individual fields are adjusted based on range condition monitoring. If condition is declining, stocking rate for that field is reduced.

4. How do you make stocking-rate decisions in an individual year?

- **PFRA Pastures**
  - PFRA uses information such as fall precipitation and winter snowfall to forecast the growing conditions in the coming season, and uses this information in making agreements with pasture patrons.
  - They may or may not fill vacancies among patrons, depending on the forecast.
  - They adjust the date for beginning of grazing (the take-in date) depending on the forecast.
  - They guarantee 100 days of grazing, but beyond this may adjust the length of the season depending on production levels.

- **Saskatchewan Provincial Pastures**
  - Provincial Pastures likewise use information from the fall and winter to forecast production in the coming season.
  - They inform patrons during the winter about probable changes in stocking, but make a final decision on approximately May 1.
  - They do not like to reduce the length of the grazing season, because it causes problems for patrons if cattle come home early (e.g. before they can be turned out on stubble). They prefer to reduce the number of cattle for each producer, and keep them for the full season.

- **Saskatchewan Co-op Pastures**
  - Co-op Pastures do not have a formal process for making year-to-year adjustments.
  - Patrons have an annual meeting and make decisions among themselves about adjusting stocking for the coming year.

- **Private Producers**
  - Private producers likewise use information such as fall precipitation and winter snowfall to forecast conditions for the coming season and adjust stocking rates if necessary.
  - Often the first year of a drought does not require major adjustments if there is adequate carryover. After that first year, producers try to forecast whether there will be a second drought year.

5. If you have to reduce your stocking rate in an individual year, how do you do it?

- **PFRA and Provincial Pastures**

- Community pastures can make administrative decisions to reduce stocking rates. The onus is on the patrons to find alternative grazing to make up for reduced access to pastures.
- The methods of reducing stocking rates include:
  - Not filling vacancies among patrons.
  - Reducing the number of cattle accepted from each patron.
  - Beginning grazing later in the spring.
  - Ending grazing earlier in the summer.
- In some ways, community pastures have less flexibility than private producers. They can adjust the number of cattle before the grazing season starts, but once they have accepted delivery, the only thing they can adjust is the length of the grazing season.
- Community pastures have intentionally conservative stocking rates, so probably do not track weather cycles as closely as they could. In good years, they do not add as much grazing as the production could support.

- **Private producers**
  - Private producers have several different methods that can be used to reduce stocking in dry years:
    - Heavier culling of herd than would normally be done in a given year.
    - Using feeders as part of the herd, and selling them during dry years.
    - Finding alternative grazing land, e.g.

        - Renting grazing land in other regions or provinces with better moisture. Crown Lease Land in these regions may be allowed to take in additional stock to assist producers in drier areas.
        - Indian Reserves
        - Wildlife Lands (emergency grazing programs)
    - Keep some portion of their own grazing land as a reserve for use in dry years.
    - Fence some cropland (or use cropland that is already fenced) , and sow an annual crop to be used for grazing.
    - During years of poor crop production, turn cattle out on crops rather than harvest them. Saskatchewan Crop Insurance facilitates this—they require that a sample area in the crop be kept for inspection by adjusters, but the rest of the field can be grazed.
    - Building up stockpile of feed (more than would normally be needed in a given year).
    - Buying more feed than normal (but price of feed goes up in dry years when demand is high).
- Producers will usually use heavier culling plus one of the other strategies.
- Producers in drier regions (Brown Soil Zone) have more frequent drought, and therefore tend to have emergency plans in place, such as making contacts with landowners in other regions that may provide alternative grazing. They maintain larger feed reserves, and they tend to graze more conservatively, maintaining more litter cover which provides some protection during drought years. Producers in moister regions do not plan for drought as much because it is typically less frequent. They tend to graze more heavily because they usually do not have to maintain litter cover, and they do not build up more than a year's supply of feed because it would just rot.

RESEARCH RESULTS: The results of the modelling work described in the current report were presented to the workshop participants.

GROUP DISCUSSION: What will be the impacts of climate change on grazing operations, and how can they adapt to it?

1. **<u>What will climate change mean for grazing operations?</u>**
    - The models do not indicate a major reduction in grass production under climate change. This should mean than grazing operations have a long-term future in the Canadian Prairies.
    - Future climate may be less suitable for annual crop production in drier portions of the Prairies. If this happens, there could be more conversion of marginal cropland to perennial forage. This would further increase the importance of grazing operations.
    - Increased conversion to perennial forage could increase the demand for cultivars or ecovars of native grasses.
    - Climatic warming may lead to a northward shift in the forest/grassland boundary. Marginal forests could become more open and gradually become grassland. This could again increase the resource for the grazing industry.
    - There will probably be an increase in warm-season grasses, that may increase productivity because of higher water use efficiency. However, this will vary with the

species and site. On loam and clay soils, the main warm-season grass is blue grama, which is a low producer, so shift to warm-season species may not increase productivity. But little bluestem could also increase on these sites, and it is a high producer although it is less palatable than the other midgrasses. On sandy soils, the main warm-season grass is sand grass, which is a high producer but is also less palatable than the cool-season grasses.

- Under a warmer climate, there should be a longer grazing season, which means a shorter feeding season. This will be an advantage for producers because it will reduce the requirement for putting up or purchasing feed. However, grazing for a longer season with the same annual production just means that you can support fewer cattle.
- In a warmer climate, it may be even more important to maintain litter cover to protect the soil against direct evaporation.
- There may be more heat stress on cattle in hotter summers.
- There may be more disease problems in a warmer climate.
- We also need to look at water resources. If climate change were to reduce the supply of water in wells or dugouts, this could have a larger impact on grazing operations than any change in grass production.
- Hay crops should be affected by the same trends as grazing land production. Timing of moisture supply is critical for hay production—moisture must be available early in the season. Any reduction in streamflow could reduce the water supply for forage irrigation.

2. How can grazing operations adapt to climate change?

- **Plant Species**
  - Maybe we should be seeding more warm-season grasses that will be better-adapted to the warmer climate.
  - However there is controversy over introducing new species that could cause problems with exotic invasion.
  - But we already have some warm-season grasses that could be increased. Also, warm-season grasses from further south may get here eventually, so seeding them will just speed up the process.
  - Priority of acceptability should be:
    1. Warm-season grasses that are already here.
    2. Warm-season grasses that are native in other parts of North America (further south in the Great Plains)
    3. Warm-season grasses that are not native to North America.
  - Maybe there will be more use of warm-season forages (e.g. corn) on cropland.

- **Water Resources**
  - If water resources are reduced by climate change, there may be a need for more drilling and water pipelines.

- **Monitoring**
  - Monitoring programs are needed to detect long-term changes in productivity that are related to climate change.

- The range benchmark system is important for this purpose. Alberta has a well-developed benchmark system, but in Saskatchewan only the sites started by PFRA are being monitored.
- It is difficult to maintain funding for long-term monitoring because political priorities tend to be short-term. Monitoring programs have to be simple and low-cost.
- Maybe we should be involving producers or other volunteers in monitoring. For example, there are forage and grazing clubs in some areas. Student groups (e.g. Range Club at University of Saskatchewan) could also be involved.