Impact of climate change scenarios on the agroclimate of the Canadian prairies

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McGinn, S. M. and Shepherd, A. 2003. **Impact of climate change scenarios on the agroclimate of the Canadian prairies.** Can. J. Soil Sci. **83**: 623–630. Regional climate change scenarios for the Canadian prairies were generated using historic weather data and daily data from two Canadian Climate Centre general circulation models (GCM). Model CGCM1-A was a recent version release while its predecessor was model GCMII. The GCM data were combined with historic values to generate two additional scenarios. All scenarios were used to drive the modified Versatile Soil Moisture Budget model that assessed soil moisture, aridity and other agroclimatic indices. The modelled results for all scenarios were compared to those using the historic climate data. The model predicted earlier seeding dates for spring wheat between 18 and 26 d. Early seeding and harvest was shown to be an appropriate adaptive strategy that avoided more arid conditions in the late summer. The soil water deficit was lower under GCMII than historic values by 46 mm. For CGCM1-A, the soil water deficit was decreased by 8 mm across the Prairie Provinces compared to historic values. GCM scenarios predicted unchanged or increased soil water in the top 120 cm soil across the Canadian prairies compared to the historic scenario. There were some regions such as southeastern Saskatchewan and southern Manitoba where reductions in summer rainfall (for CGCM1-A) were large. These regions experienced the greatest benefit of earlier seeding dates.

Key words: Climate change, agriculture, aridity, growing degree-days, soil moisture, seeding date, harvest date

McGinn, S. M. et Shepherd, A. 2003. **Incidence de différents scénarios relatifs au changement climatique sur l'agroclimat des Prairies canadiennes**. Can. J. Soil Sci. **83**: 623–630. Les auteurs ont produit plusieurs scénarios sur le changement climatique qui pourrait affecter la région des prairies canadiennes à partir de données météorologiques historiques et quotidiennes grâce à deux modèles de circulation générale (MCG) du Centre climatologique canadien, en l'occurrence le modèle CGCM1-A, une version récente, et son prédécesseur, le modèle GCMII. Les données des MCG ont été combinées aux valeurs historiques pour produire deux autres scénarios. Ensuite, les auteurs ont appliqué ces scénarios à une variante du modèle *Versatile Soil Moisture Budget* (bilan polyvalent de l'eau du sol) pour estimer la teneur en eau du sol, l'aridité et d'autres indices agroclimatiques. Ils ont comparé les résultats du modèle pour les différents scénarios à ceux obtenus avec les valeurs historiques. Selon le modèle, on pourrait commencer à semer le blé de printemps 18 à 26 jours plus tôt. Avancer semis et moisson est une stratégie d'adaptation adéquate, car on éviterait les jours plus secs de la fin de l'été. Le GCMII prévoit un déficit hydrique de 46 mm inférieur aux valeurs historiques. Avec le CGCM1-A, le déficit hydrique diminue de 8 mm par rapport aux valeurs historiques dans l'ensemble des provinces des Prairies. Toujours d'après les scénarios du MCG, dans les prairies canadiennes, la quantité d'eau présente dans la couche supérieure de 120 cm du sol ne changera pas ou devrait augmenter comparativement aux données historiques. Certaines régions comme le sud-est de la Saskatchewan et le sud du Manitoba souffriront d'une importante baisse des précipitations en été (CGCM1-A). Ces régions sont celles qui bénéficieront le plus de semis plus précoces.

Mots clés: Changement climatique, agriculture, aridité, degrés-jours de croissance, teneur en eau du sol, date de semis, date de récolte

Canadian prairie agriculture involves a high degree of management but is still susceptible to failure under extremes in weather. As such, there is a need to continuously evaluate farming practices and implement those that minimize deleterious elements of weather and take advantage of conditions that promote production and food quality. With the likelihood of climate change, possibly within our lifetime, agricultural practices will require further adjustment to meet the new climate constraints on food production. However, understanding the vulnerability of agriculture to climate change, and subsequently developing adaptation strategies, can only be accomplished with some prior understanding of the magnitude in expected climate change, e.g., best-to worst-case scenarios.

With the predicted global warming of 1.4 to 5.8°C between 1900 and 2100 (Intergovernmental Panel on Climate Change 2001), insights on the impact of warming on sustainability of agriculture are needed at regional scales. Since adaptive strategies can only be developed given sufficient lead time, there is some urgency to estimate the susceptibility of agriculture to climate change. In Canada, understanding the vulnerability of agriculture in the prairie region is critical since this area accounts for 82% of the cultivated land in Canada and is an important supplier of food for the global community (Parry 1990). Canada is identified to become even more prominent as a supplier of food with projected climate change (International Insitute for Applied Systems Analysis 2001).

With climate warming on the Canadian prairies, there is potential to develop more diverse cropping systems where

Abbreviations: **GCM**, General Circulation Model; **GDD**, growing degree-days; **mVSMB**, modified Versatile Soil Moisture Budget relatively short growing season and soil moisture under dryland conditions now limit crop yield potential. However, along with warming, there is uncertainty in the prediction of soil moisture for crop production. Although GCM provide information on soil moisture, these data are generally useful in agricultural impact studies only when they are downscaled to a regional resolution. One means of accomplishing this is to use a regional GCM model (e.g., Laprise et al. 1998). Another method is to downscale meteorological parameters from GCM output to a regional scale, like temperature and precipitation, and then use them to drive a water balance model that can predict soil moisture.

The modified Versatile Soil Moisture Budget (mVSMB) model has been used successfully for predicting soil moisture in various soil layers at a daily time step (Akinremi et al. 1996; Akinremi and McGinn 1996). This model was validated at a regional level (Akinremi et al. 1997) and was in agreement 60% of the time (using 145 sites) in 5 yr out of 8 yr. The agreement was higher than expected (due to chance alone) in all 8 yr tested (Akinremi et al. 1997). Associated with the mVSMB model is a crop growth module that also estimates evapotranspiration over the growing season.

A previous study for Alberta, using the Canadian Centre for Climate Modeling and Analysis second generation General Circulation Model (GCMII) for a doubling of CO_2 concentration, reported a 4.3ºC temperature increase and 28% increase in annual precipitation (McGinn et al. 1999). For the entire Canadian prairies, the same GCMII simulation predicted a 5 to 7°C increase in temperature and a 15% increase in precipitation (Saunders and Byrne 1994).

The impact of climate change on agriculture in the Canadian prairies will depend on the predicted magnitude, seasonality and variability in both temperature and precipitation. It follows that as GCM predictions are revised, reflecting a greater understanding of the climate driving factors, there is a need to revisit potential impact and adaptation work in agriculture. The objective of our study was to compare the vulnerability of agriculture, using agroclimatic indicators, to predictions of climate change across the entire Canadian prairies. This was accomplished using a range of four climate change scenarios. These scenarios were generated using model output (GCMII and CGCM1-A) developed at the Canadian Centre for Climate Modelling and Analysis.

MATERIALS AND METHODS

Climate Scenarios

Five climate databases were developed (Table 1) that included a database of historic weather data and four climate change scenarios. All data were scaled to a common grid size of 50 by 50 km across the agriculture regions of the Canadian prairies using an approach given by McGinn et. al. (1999). The historic database consisted of daily maximum and minimum air temperature, precipitation and solar radiation between 1960 and 1989. These data were derived from 142 weather stations (Meteorological Service of Canada, Environment Canada) across the Canadian Prairies. Each weather station record consisted of at least 20 yr of data, where at least 80% of the time series was intact. Missing data were estimated from neighbouring data, adjusted by the historic station-to-neighbour difference (temperature) and ratio (precipitation) (McGinn et. al. 1999). Gaps in the solar radiation data series were estimated using sunshine duration (Barr et. al. 1996).

Table 1. Combinations of climate data elements used to generate four climate change scenarios and a historic climate database

	GCMII	CGCM 1-A	GCMII_ HP	CGCM1- A_HP	Historic
Historic temperature					x
Historic precipitation			x	x	x
GCMII temperature	x		x		
GCMII precipitation	x				
CGCM1-A temperature		x		x	
CGCM1-A precipitation		x			
Historic solar radiation	x	x	x	x	x

The regional scenarios were generated using data from the Canadian Centre for Climate Modeling and Analysis second generation General Circulation Model (GCMII), and the first generation coupled GCM model with atmospheric aerosols (CGCM1-A). Both models were driven using the projected emission scenario IS92a (IPCC 2001). Differences between the two GCMs are outlined by Hengeveld (2000). The newer CGCM1-A model used GCMII to simulate atmospheric circulation (10 vertical levels). However, CGCM1-A used a modular ocean model (MOM) that simulated 29 vertical layers (horizontal resolution of about 200 km). Both GCMII and CGCM1-A used a thermodynamic sea ice model. The CGCM1-A also incorporated a land surface model for determining a simple water balance of soil.

Differences between output data were tabulated from the GCM simulations using the doubling of the 1980 CO_2 concentration (2×) and the 1980 CO_2 concentration (1×). Tabulated data included maximum and minimum air temperature, and the ratio of 2× to 1× precipitation, for each GCM (coarse) grid node (3.71° latitude by 3.75° longitude). These data were then downscaled to a common finer grid of approximately 50 by 50 km (9 by 5 grid points per GCM grid). The interpolated data at the fine grid scale were generated using the nearest-neighbour approach where each neighbour estimate was weighted by the inverse-distance-squared method. The same gridding procedure (including solar radiation) was carried out for the historic weather records where a maximum distance for temperature and precipitation was 70 km, and 350 km for solar radiation. The historic data and GCM parameters at each fine grid point were used to develop the regional climate change scenarios.

The new daily temperature data were calculated by adding to the historic temperature values the difference between the temperature generated using the 2× and 1× CO_2 concentration simulation runs. For precipitation, the ratio of the mean monthly total for the 2× and 1× simulation runs was multiplied by the historic mean monthly total to generate a new mean monthly total, P*. The historic daily precipitation was adjusted using the ratio of P* to the actual monthly total. In this manner, the amount of precipitation changed but not the frequency distribution over the month.

In addition, a combination of each GCM temperature and the historic precipitation (HP) amount and frequency were used to generate a third (GCMII_HP) and fourth (CGCM1-A_HP) climate change scenario.

The range in climate scenario data was used to invoke different impacts on agroclimatic indices and indicate the vulnerability of prairie agriculture to some best- and worst-case scenarios. In addition, using sequential GCM versions allowed evaluation of the impact of these GCM changes on agriculture.

Agronomic Models

The five climate databases were used in conjunction with a modified Versatile Soil Moisture Budget, mVSMB, (Akinremi et. al. 1996; McGinn et al. 1999) to document seeding date, harvest date, degree-days, accumulated precipitation, accumulated actual evapotranspiration, accumulated potential evapotranspiration and daily average moisture content. The mVSMB model was used to simulate the growth and water use of spring wheat (*Triticum aestivum* L.). All the output parameters were accumulated between the dates calculated for seeding and harvest and were averaged for each province for the 30 yr period. In mVSMB, seeding date was determined following 10 d when specific criteria were met, i.e., mean daily air temperature > 10°C, precipitation < 2 mm, snow-on-ground < 10 mm, and soil water < 90% of available water-holding capacity (McGinn et al. 1999). Harvest was estimated using the biometeorological time scale (Robertson 1968). This model uses maximum and minimum air temperatures, and photoperiod, to determine five stages of growth in spring wheat from emergence to grain ripening. Growing degree-days (GDD) was calculated by mVSMB between seeding and harvest using a base temperature of 5°C. As such, our reported GDD values would be less than those reported for an entire calendar year.

The mVSMB is a water-budgeting model requiring daily weather input and regional soil data. It simulates variation in soil moisture content using accepted concepts of water movement in the soil and water loss through soil evaporation and transpiration from crops (Baier et. al. 1979). The water requirement of the crops in relation to the atmospheric conditions is simulated through crop coefficients for different phenological stages of crop.

Potential evapotranspiration was determined using the approach reported by Priestley and Taylor (1972) that required knowing the net radiation, derived in our study from incoming solar using the method described by Linacre (1993). Actual evapotranspiration was determined by the estimated water extracted from each soil layer. In this process, the potential evapotranspiration was divided between soil layers using a crop water extraction coefficient (fraction of total lost per soil layer), then the value in each layer was adjusted for stage of growth and water stress within each soil layer (ratio of actual water content to water-holding capacity).

The available water-holding capacity of soils, required as input to mVSMB, was obtained for all fine grid points across the Canadian prairies. Previously these data were on file for Alberta (McGinn et. al. 1999) while those for Saskatchewan and Manitoba required downloading from the Canadian Soil Inventory System (Shields et. al. 1991). This was accomplished using a geographical information system to extract the digitized soil data by overlaying soil polygon data with grid point locations.

The mVSMB model output driven by the five climate databases was summarized by province (Alberta, Saskatchewan and Manitoba) and northern and southern regions within each province. The north-south boundary was set at latitude 53.38°N. The north-south boundary was roughly based on the transient in vegetation in Alberta where the prairie changes to a more forested landscape. Alberta was divided into 61 northern and 99 southern grid points, Saskatchewan divided into 22 northern points and 127 southern, and Manitoba divided into 7 northern and 52 southern. The smaller number of northern grid points is a result of the sparse number of northern climate stations. In such a situation, the threshold distances could be exceeded resulting in no data for many grid nodes.

Adaptive Strategy

The management decision of when to seed and harvest was predicted using algorithms within mVSMB based on the weather. As a result, these decisions were automatically adapted to the changes imposed by the different GCM scenarios. The impact of adapting the seeding date to each GCM scenario was investigated by substituting in the seeding date predicted for the historic climate scenario as the start date for the biometeorological time scale. The averaged daily soil moisture value from this "forced" seeding date simulation was compared to that from the mVSMB run with adaptive seeding dates.

Aridity Index

Two methods were used to estimate aridity, i.e., the supplementary water needed to maintain non-water-limited crop growth over a growing season. The aridity 1 index indicated the water shortage based on the daily difference between available soil water content and 50% of the available water-holding capacity (Shields and Sly 1984). When the daily averaged available soil water declines below 50% of the available water-holding capacity of the soil, the difference is calculated and summed over the growing season. The aridity 2 index was based on the accumulated daily difference between actual and potential evapotranspiration, and quantifies the soil-water limitation to evapotranspiration.

Each aridity index was calculated for each climate database at all grid points, and provincial averages were then tabulated as for the other agroclimatic indices.

Climate Classification

The classification of climate used in our study follows that given by Thornthwaite (1931) and used by Williams et. al. (1988) to evaluate the effect of climate change in Saskatchewan. The index is a measure of climate influenced vegetation classes and is calculated as:

$$I = \sum_{i=1}^{n} 115\left(\frac{P_i / 25.4}{1.8T_i + 22}\right)^{1.11} \tag{1}$$

Table 2. Mean yearly temperature and total precipitation generated by the historic, GCMII and CGCM1-A climatic scenarios for the agriculture prairie region. Values in parentheses indicate the change from the historic values

Element	Historic	GCMII	CGCM1-A
Minimum temperature (°C)	–4.1	1.2 (5.3)	0.9 (3.2)
Maximum temperature (°C)	8.1	13.1 (5.0)	11.0 (2.9)
Precipitation (mm)	454	600 (32%)	475 (4%)

where P is the mean monthly precipitation (mm), T is the mean air temperature (°C), an i is the month (1 to 12). Thornthwaite (1931) used Eq. 1 to estimate the ratio of precipitation to potential evaporation. When this ratio is high, precipitation exceeds evaporation, which coincides with a more humid climate; the smaller ratio relates to an arid climate. This ratio is also useful in delineating native vegetation as it relates to climate. The Thornthwaite values of 32–63 indicate a sub-humid climate (grassland), and values of 16–31 indicate a semi-arid climate (steppe).

RESULTS AND DISCUSSION

Temperature and Precipitation

The spatial and temporal patterns of the historic, GCMII and CGCM1-A outputs were reported by Shepherd and McGinn (2003) and are summarized in Table 2. Minimum and maximum air temperature are predicted to increase (above 1960–1989 historic values) by 5.3 and 5.0°C under GCMII, respectively, and by 3.2 and 2.9°C under CGCM1-A, respectively. Total annual precipitation is predicted to increase by 32% (GCMII) and 4% (CGCM1-A) above historic values. However, there was considerable spatial variability in precipitation across the Canadian prairies, where the western regions show a marked increase (Shepherd and McGinn (2003)).

Seeding and Harvest Dates

Using historic climate data, mVSMB predicted a provincially averaged seeding date of 19, 21 and 24 May for Saskatchewan, Manitoba and Alberta, respectively (Table 3). The earliest harvest date occurred in Saskatchewan on 27 August, followed by Manitoba a day later and Alberta (12 d later than Saskatchewan). On average it took 102 d to grow a spring wheat crop in the prairies.

For all GCM scenarios, Saskatchewan had the earliest seeding dates ranging from 20 April to 1 May (DOY 110 to 121) compared to Manitoba (27 April to 5 May; DOY 117 to 125) and Alberta (28 April to 4 May; DOY 118 to 124). The advance in seeding date across all three Prairie Provinces ranged for all climate scenarios from 18 (CGCM1-A_HP; least warming and historic precipitation) to 26-d (GCMII_HP; greatest warming and historic precipitation). The advance in seeding date for CGCM1-A_HP scenario was similar to that of the CGCM1-A (18–19 d) while a more intermediate advanced seeding date (21 d) is predicted for GCMII (greatest warming with greatest increase in precipitation). For GCMII_HP, a 26-d advance in seeding date was predicted. Earlier seeding dates reflect the predicted higher maximum and minimum air temperatures in the GCM data.

In all GCM scenarios, the spatial variability of the seeding date (on average 9 to 12 d across all three provinces) increased relative to that of the historic average (about 6 d). Historically, Alberta had the highest spatial variability reflecting the more northern extent of the data grid (and agricultural region). However, Saskatchewan and Manitoba showed the largest increase from historic values.

Harvest dates in Alberta were advanced by between 22 (CGCM1-A_HP) and 34 d (GCMII_HP). These same two scenarios were responsible for advancing Saskatchewan's harvest date by 23 to 36 d, respectively, and Manitoba's harvest date by 24 to 37 d. The earlier harvest dates are expected using the GCM scenarios since the seeding dates were also earlier. However, the average duration between seeding and harvest for each GCM scenario was 5 to 11 d shorter than that for the historic scenario. The shorter period needed to reach crop maturity under the GCM scenarios is attributed to accrued biometeorological units driving the phenological development that resulted from higher daily air temperatures. A shorter maturity time (due to higher temperature) was reported by Laurila (2001) to decrease grain yield of spring wheat. The spatial variability for harvest date was also increased for GCM scenarios but the increase was less than that found for seeding date.

In all provinces under the historic climate, the seeding and harvest dates for the southern region (below 53.38°N) were earlier than those in the north by an average of 6 and 7 d, respectively. Under the GCM scenarios, the above pattern remained the same but the north–south difference was greater. The difference was greatest for scenario GCMII_HP, up to 21 d earlier in the south relative for seeding and 14 d earlier for harvest, compared to the north. The north–south differences in Saskatchewan and Manitoba were larger than those for Alberta.

Growing Degree-days

Historically, Manitoba and Saskatchewan had the highest GDD accumulations for the growing season, 1183 and 1154, respectively, followed by Alberta with 984 (Table 4). This lower value coincides with an elevation effect on air temperatures found in Alberta where the plains slope gradually eastward dropping some 900 m (equivalent to 9°C cooling following the dry adiabatic lapse rate) between Alberta foothills and eastern Manitoba (Padbury et al. 2000). The historical seeding and harvest dates and GDD may also be partly influenced by the higher summer minimum temperatures found further east (Shepherd and McGinn 2003). The accumulated GDD in the southern prairie (below 53.38ºN) were 1.5% higher than those for the provinces as a whole (Table 4), reflecting a small latitude effect.

Each GCM scenario generated an increase in the number of GDD over the growing season in each province. The change in GDD ranged between 94 and 217 under the GCMII (including GCMII_HP), and between 38 and 155 under CGCM1-A (including CGCM1_HP). GCMII scenarios, with both simulated and historic precipitation data, were associated with the greatest temperature increase compared to the CGCM1-A incorporated scenarios, and also generated the greatest accumulated GDD values over the growing season.

Table 3. Average provincial seeding and harvest dates for five climate scenarios. Values in paratheses are standard deviations associated with the spatial variability about the provincial average

	GCMII	CGCM1-A	GCMII_HP	CGCM1-A_HP	Historic
			Seeding date (DOY)[z]		
Alberta	123 (12.2)	122 (12.1)	118 (13.0)	124 (10.6)	144 (9.0)
Saskatchewan	114 (12.8)	120 (10.1)	110 (13.7)	121 (9.1)	139 (4.8)
Manitoba	122 (8.3)	124 (7.9)	117 (9.3)	125 (7.3)	141 (3.7)
Mean	120 (11.1)	122 (10.0)	115 (12.0)	123 (9.0)	141 (5.8)
			Harvest date (DOY)		
Alberta	220 (16.2)	227 (15.2)	217 (16.1)	229 (15.5)	251 (9.3)
Saskatchewan	205 (9.5)	215 (7.4)	203 (9.4)	216 (7.4)	239 (7.5)
Manitoba	207 (7.0)	215 (6.8)	203 (7.3)	216 (6.6)	240 (5.5)
Mean	211 (10.9)	219 (9.8)	208 (10.9)	220 (9.8)	243 (7.4)

[z] DOY = day of the year.

Table 4. Averaged accumulated growing degree-days by province (for agriculture regions) under four climate scenarios that coincide with advances in seeding and harvest dates, and for historic climate data coinciding with historic seeding and harvest dates. Values in paretheses are standard deviations of the spatial averages

			Growing degree-days		
	GCMII	CGCM1-A	GCMII_HP	CGCM1-A_HP	Historic
Alberta	1201 (75)	1132 (95)	1194 (68)	1139 (92)	984 (179)
Saskatchewan	1273 (52)	1203 (43)	1264 (55)	1210 (38)	1154 (56)
Manitoba	1301 (45)	1221 (40)	1277 (42)	1230 (37)	1183 (59)
Mean	1258 (57)	1185 (59)	1245 (55)	1193 (56)	1107 (98)

Under each GCM scenario, Manitoba's growing season had the highest number of GDD of the provinces, yet the smallest increase from historic values. Manitoba's GDD increased between 38 and 118 above historic values similar to that found in Saskatchewan (49 to 119). In Alberta, GDD was increased between 148 and 217 above historic values. Under each GCM scenario, Alberta also experienced one of the smallest decreases in the length of the growing season relative to the historic scenario. It is reasonable to expect that the relatively longer growing season in Alberta under climate change would account for the relatively larger increase GDD under climate change compared to the historic scenario. When GDD were averaged for grid points below 53.38°N for GCM scenarios, there was only a slight increase in the seasonal accumulation of GDD of 0.9 to 1.3% relative to the averaged provincial values. This indicates GDD increase was fairly uniform across the provinces.

The historic spatial variability in Alberta (179 GDD) was much larger than that for Saskatchewan (56) or Manitoba (59), perhaps reflecting the more northerly grid points found in Alberta (a result of a more northerly dense climate station network coinciding with a northern agriculture region). The spatial variability in GDD decreased for each GCM scenario relative to the historic values. This may be an artefact related to downscaling GCM data, i.e., spatial smoothing of temperature data.

Simulations were run for all climate change scenarios where the seeding date from the historic climate scenario was used instead of the seeding date associated with earlier spring warming under each climate change scenario. The impact of advancing the seeding date caused a reduction in the accumulated GDD value for the climate change scenarios. In Alberta, the GCMII scenario GDD value decreased by 200, while in Saskatchewan and Manitoba it decreased by 400. In Alberta, CGCM1-A scenario GDD value decreased by 100, and in Saskatchewan by 200 and in Manitoba by 300.

Soil Moisture

Generally, the most critical parameter for crop growth on the semi-arid Canadian prairies is the availability of soil water. The historic mean daily soil moisture content is 82 mm in the upper 120 cm of soil (Alberta), 47 mm (Saskatchewan) and 76 mm (Manitoba) (Table 5). The low value for Saskatchewan coincides with Saskatchewan having the lower annual precipitation (395 mm compared to 482 mm for Alberta and 486 mm for Manitoba; Shepherd and McGinn 2003). In addition, the ratio of actual evapotranspiration to potential evapotranspiration (ET_a/ET_p) indicates the relative limiting factor to crop growth by limiting water resources. The historic values of this ratio are 0.69 (Alberta), 0.54 (Saskatchewan) and 0.69 (Manitoba), i.e., the value of ET_a relative to ET_p is less in Saskatchewan than in Alberta or Manitoba, implying greater water stress in Saskatchewan.

Historically, daily average soil moisture is higher in northern Alberta than in the south (90 and 77 mm per 120-cm soil depth, respectively), does not vary between north and south in Manitoba and is only slightly higher in southern Saskatchewan than in the northern region. The relatively large difference in soil moisture between northern and southern Alberta is consistent with the relatively large difference in precipitation across Alberta.

For model runs using the GCM scenarios, the combination of temperature and precipitation change had an impact on soil moisture. In each scenario, Saskatchewan had the lowest soil moisture (47 to 66 mm per 120-cm soil depth), while

Table 5. Provincial data on (a) average daily soil moisture throughout the growing season, and (b) increase in average daily soil moisture in response to earlier seeding dates. Values in parentheses are standard deviations of spatial averages

(a)	Average daily soil moisture (mm/120-cm soil depth)				
	GCMII	CGCM1-A	GCMII_HP	CGCM1-A_HP	Historic
Alberta	100 (37)	81 (33)	74 (30)	73 (30)	82 (40)
Saskatchewan	66 (21)	51 (16)	47 (15)	47 (15)	47 (14)
Manitoba	102 (39)	82 (29)	75 (26)	75 (26)	76 (28)
Mean	89 (32)	71 (26)	65 (24)	65 (24)	68 (27)

(b)	Average daily soil moisture increase (mm) attributed to a shift to an earlier seeding date			
	GCMII	CGCM1-A	GCMII_HP	CGCM1-A_HP
Alberta	8	2	5	1
Saskatchewan	11	9	8	6
Manitoba	16	15	15	12

Alberta and Manitoba had similar amounts (73 to 102 mm per 120-cm soil depth); note that these are province averages.

The CGCM1-A scenario increased the average growing season soil moisture in Saskatchewan and Manitoba by about 8% but had little effect on that for Alberta. The CGCM1-A_HP scenario (using historic precipitation) had little effect on soil moisture in Manitoba and Saskatchewan, but reduced Alberta's soil moisture from 82 to 73 mm per 120-cm soil depth (a reduction of 11%). The reduction in Alberta's soil moisture in CGCM1-A_HP is reflective of an increase in the growing season actual evapotranspiration by 4 mm, whereas the value for Saskatchewan and Manitoba decreased by 23 and 28 mm, respectively.

The GCMII scenario, when used to drive the soil moisture model, showed a substantial increase in the average daily soil moisture (18% in Alberta, 29% in Saskatchewan, 26% in Manitoba). These increases coincide with the predicted increase of seasonal precipitation (29, 30 and 36% across Alberta, Saskatchewan and Manitoba, respectively). GCMII_HP (using historic precipitation) resulted in a predicted slight decrease in the soil moisture of Saskatchewan and Manitoba, but a larger decrease in Alberta (10%), similar to that of CGCM1-A_HP.

The soil moisture difference between north and south regions of each province where generally consistent under all climate scenarios. In Alberta, the northern region had more soil moisture than the south; the historic difference was 12 mm (daily average in 120 cm) and for the GCM scenarios it ranged from 12 to 17 mm higher in the north. In Saskatchewan, the southern region was predicted to have more soil moisture than the north (historic difference was 6 mm and the GCM scenario differences ranged from 5 to 14 mm). Although northern Saskatchewan received more annual precipitation, actual evapotranspiration was also greater. In Manitoba, the north–south difference in soil moisture was only 0.5 mm for the historic scenario (northern region higher). For the GCM scenarios for Manitoba, the southern region had higher soil moisture ranging from 3 to 12 mm. Overall, Alberta displayed the greatest difference between north and south soil moisture content, the south being more arid by a difference of 15 mm per 120 cm soil depth for all GCM scenarios.

The impact of advancing seeding date, from the later (historic) seeding date, on soil moisture for each climate change scenario was evaluated (Table 5b). For GCMII, average daily soil moisture through the growing season increases by 8, 11 and 16 mm per 120 cm soil depth in Alberta, Saskatchewan and Manitoba, respectively. Under CGCM1-A soil moisture increased by 2, 9 and 15 mm per 120-cm soil depth in Alberta, Saskatchewan and Manitoba, respectively, with a shift to earlier seeding. The GCM scenarios using the historic precipitation amounts had slightly less of an increase in soil moisture compared to GCM with simulated precipitation.

Aridity

Historically, the prairie-wide aridity 1 deficit of 165 mm was greater than that given by aridity 2 at 128 mm (Table 6). This was consistent across each prairie province, e.g., Alberta aridity 1 deficit was 148 mm compared to 117 mm for aridity 2, Saskatchewan's deficit was 203 and 157 mm, and Manitoba's 143 and 109 mm for aridity 1 and aridity 2, respectively. Differences between aridity 1 and 2 are expected as a result of the way non-stress conditions are express. In the case of aridity 1, 50% of the available water-holding capacity is used as the non-stress delimiter, whereas for aridity 2 it is the potential evapotranspiration. These two delimiters are related, e.g., potential evapotranspiration coincides with high soil moisture. In both indices, large deficits reflect water stress and therefore reduced growth and grain yield.

The lowest aridity values occur under the GCMII scenario using simulated precipitation, which is consistent with the increased precipitation this scenario produces. Aridity values for Alberta, Saskatchewan and Manitoba are 105, 149 and 102 mm (aridity 1), respectively, and 84, 114 and 79 mm (aridity 2). On average across the three Prairie Provinces, water deficit over the growing season decreased between 46 and 36 mm for aridity 1 and 2, respectively. Aridity values for the growing season under other scenarios were closer to the historic values. Scenario CGCM1-A generated slightly lower water deficits of 4 to 8 mm (less arid conditions) while for the scenarios with historic precipitation (GCMII_HP and CGCM1-A_HP) Alberta was shown to become more arid than Saskatchewan or Manitoba.

Under all scenarios, including the historic, Saskatchewan had much higher aridity values than other provinces, i.e., implying greater plant water stress in Saskatchewan.

Table 6. Accumulative growing season aridity values (mm water deficit) for different climate scenarios. Values in parentheses are the standard deviations of the spatial averages

	Aridity 1 (mm)				
	GCMII	CGCM1-A	GCMII_HP	CGCM1-A_HP	Historic
Alberta	105 (48)	145 (56)	149 (52)	154 (54)	148 (89)
Saskatchewan	149 (24)	194 (28)	194 (32)	194 (30)	203 (32)
Manitoba	102 (34)	133 (30)	138 (27)	134 (26)	143 (29)
Mean	119 (35)	157 (38)	160 (37)	161 (37)	165 (43)
	Aridity 2 (mm)				
	GCMII	CGCM1-A	GCMII_HP	CGCMI-A_HP	Historic
Alberta	84 (32)	115 (43)	118 (40)	123 (42)	117 (47)
Saskatchewan	114 (20)	153 (26)	155 (26)	157 (26)	157 (27)
Manitoba	79 (24)	103 (23)	107 (22)	109 (20)	109 (22)
Mean	92 (25)	124 (31)	127 (29)	130 (29)	128 (32)

Table 7. Thornthwaite index values by province (mm) for different climate scenarios. Values between 16 and 31 indicate a semi-arid climate (steppe) while values between 32 and 63 indicate sub-humid climate (grassland)

	Thornthwaite Index (mm)				
	GCMII	CGCM1-A	GCMII_ HP	CGCM1- A_HP	Historic
Alberta	50	43	37	39	44
Saskatchewan	39	34	30	33	37
Manitoba	50	42	36	40	46

Climate Classification

Historically, the Thornthwaite climate classifications for Alberta, Saskatchewan and Manitoba were 44, 37 and 46, respectively (Table 7). These values indicate a sub-humid climate, with Saskatchewan being the most arid.

Under all climate change scenarios Saskatchewan had consistently the lowest values suggesting this province would continue to be the most arid of the three Prairie Provinces. All climate scenarios had the effect of lowering the Thornthwaite Index except GCMII that increased index values to 50 (Alberta), 39 (Saskatchewan) and 50 (Manitoba).

The scenario reducing the index most severely was GCMII_HP, which produced index values of 37 (Alberta), 30 (Saskatchewan) and 36 (Manitoba). Saskatchewan under climate scenario GCMII would change classification from a sub-humid grassland climate to a semi-arid landscape. For the remaining scenarios the index stays within the sub-humid class, i.e., 32 to 64.

CONCLUSIONS

The increase in air temperature under different climate change scenarios was reflected in the agroclimatic indices. With spring warming occurring earlier under climate change, there was an opportunity for the advancement of seeding dates. The provincially averaged advancement varied between 16 and 29 d depending on the chosen scenario. The CGCM1-A scenario predicted advancement of seeding by between 17 and 22 d. In more southern regions of each province, the seeding dates were advanced an additional 2 to 5 d compared to the provincial averages.

The number of GDD under GCMII was predicted to increase between 10 to 22% above historic values, while for CGCM1-A GDD increased between 3 to 15%. The two climate change scenarios using historic precipitation (GCMII_HP and CGCM1-A_HP) produced similar increases as their associated GCM scenario (GCMII and CGCM1-A). The greatest increase in GDD was found for Alberta for all scenarios, suggesting that this region would benefit the greatest from warming during the growing season (seeding to harvest).

For GCMII scenario, mVSMB predicted soil moisture to increase (above historic values) on average across all Prairie Provinces by 31% (21 mm in 120 cm depth). This coincides with the large predicted increase in precipitation. However, under a CGCM1-A climate change scenario, soil moisture status was predicted to change by only 4% (3 mm in 120 cm depth). The climate change scenarios GCMII_HP and CGCM1-A_HP resulted in a 3-mm decrease in soil moisture on average, where nearly all was attributed to a decrease in Alberta. The increase in soil moisture under GCMII and CGCM1-A scenarios was attributed in part to the advancement in the growing season dates and decreased maturity period. The shift in seeding dates was predicted to produce the greatest water savings in southern Manitoba where June to August rainfall declined (by 30 mm in CGCM1-A) or increased the least (GCMII) relative to the remaining Prairie Provinces. In this manner, the adoption of earlier seeding dates with conventional short-season crops was an adaptive strategy that resulted in water savings.

Aridity during the growing season was predicted to decrease dramatically under a GCMII scenario (wetter conditions), to only slight changes with the remaining scenarios (CGCM1-A, GCMII_HP and CGCM1-A_HP). These findings support the conclusion found for soil moisture levels. In a similar fashion, the Thornthwaite climate classification values increase to a more humid category for GCMII but generally most scenario values fall within the current climate classification of semi-humid climate (grassland).

It is clear that the impacts in out study greatly depended upon the GCM scenario version used to generate the results. New revisions, such as the CGCM1-A, although based in part on GCMII, clearly produced a different impact on the agroclimate of Prairie agriculture.

There are factors external to our study that warrant attention in the future. For example, it is expected that CO_2 concentration increase would result in an increase in water efficiency of temperate crops that would promote crop production potential in the Canadian prairies. On the negative side, surface warming will also mean the possibility of better over-winter survival (expansion in intensity or area) of many pests, weeds and diseases on the prairies. If such factors can be controlled through crop management, our study indicates that climate change, as predicted by GCMII and CGCM1-A, should enhance the potential for crop growth in the Canadian Prairies.

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