Aridity on the Canadian Plains: Future Trends and Past Variability

The pre-settlement record of prairie drought and a forecast of future aridity and what they mean for the management of soil and water resources.

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PRAIRIE ADAPTATION RESEARCH COLLABORATIVE

SUMMARY DOCUMENT **No. 03-01**

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Drifting Soil near Oyen, Alberta, May 2002

Stranded Stream Gauge near Outlook, Saskatchewan, May, 2002

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SYNOPSIS

The Prairie Ecozone is the only major region of Canada where drought is a natural hazard. Management of prairie ecosystems and soil landscapes therefore requires an understanding of past variability and future trends in regional aridity. We used instrumental and paleoclimatic records to define a baseline for prairie aridity, to evaluate the utility of modern climate normals (*i.e.* 1961-1990) as a benchmark for future climatic change, and to provide a historical context for a range of forecasts of regional aridity from Global Climate Models (GCMs). The Canadian GCM forecasts the least increase in precipitation and the largest increase in temperature and therefore, by the 2050s, an approximately 50% increase in the area of subhumid climate, and semiarid climate over a significant area, where previously the climate was only subhumid. Tree rings and lake salinity inferred from diatom assemblages record prolonged arid events and show that modern climate normals are not representative of the full range of potential climatic conditions, even in the absence of global warming. The climate of the 20^{th} century was anomalous in terms of the absence of sustained drought and the climate normal period of 1961-1990 may have been among the most benign of the past 750 years. Because both lake and tree-ring analyses recorded an abrupt amelioration of climatic conditions near the start of the instrumental record, we suggest that the immediate impacts of future global warming may be to return the prairie environment to past conditions in which persistent aridity was recorded for intervals of decades or longer.

INTRODUCTION

In southern Canada, the largest rise in mean surface temperature from increased CO_2 will occur in the western interior, according to the Canadian Centre for Climate Modelling and Analysis (Boer *et al.*, 2000). The Canadian Global Climate Model (GCM) forecasts an increase in winter precipitation for this region, with decreased net soil moisture and water resources in summer, and more frequent extreme climate anomalies, including drought. In general, natural systems react to short-term climate variability and to extreme events before they respond to gradual changes in mean conditions. Extreme and anomalous climate can exceed the coping capacity of natural systems and the design parameters of engineered structures. When climate exceeds these thresholds, the impacts of climate can be severe.

Unfortunately, the long-term forecasting of precipitation is difficult, especially for dry environments, where precipitation is variable and occasionally extreme (Hunter *et al.*, 2002). Semiarid ecosystems and soil landscapes

Rainfall over the Hand Hills, Alberta

are sensitive to fluctuations in the surface and soil water balances. Sustained periods of low precipitation and soil moisture lower the resistance to disturbance such as fire or erosion and the recovery of natural systems can take decades or centuries. In southwestern Saskatchewan, sand dunes have been active since about 1800, following severe droughts of the 1790's known from tree-ring records (Wolfe *et al*., 2001).

Because aridity is closely linked to soil erosion and land degradation, future management of prairie ecosystems and soil landscapes will require an improved understanding of past and future trends and variability in regional aridity. Land use can have greater impact on soil landscapes than climate change; forest and farm management practices enable adaptation to climate change. Any expansion of agriculture into the currently forested margins of the southern prairies will require assessment of the sensitivity of these soil landscapes to both climate change and an altered vegetation cover. To address these issues, we used instrumental and paleoclimatic records to define regional baseline aridity for the grassland ecoregions (Figure 1). The proxy and instrumental climate data were compared to a range of climate change scenarios for the next 80 years to evaluate the usefulness of historical climate reconstructions as analogs for future climate change.

DEFINING AND MAPPING ARIDITY

Aridity is simply a lack of moisture expressed in terms of mean annual precipitation and potential evapotranspiration as a ratio (P/PET) or deficit (P-PET). P/PET, the Aridity Index (AI), is the basis for classifying drylands as hyperarid (< 0.05), arid (0.05 = AI < 0.2), semiarid (0.2 = AI < 0.5) and dry subhumid (0.5 = AI < 0.65) and for identifying land at risk of desertification, "land degradation in arid, semiarid and

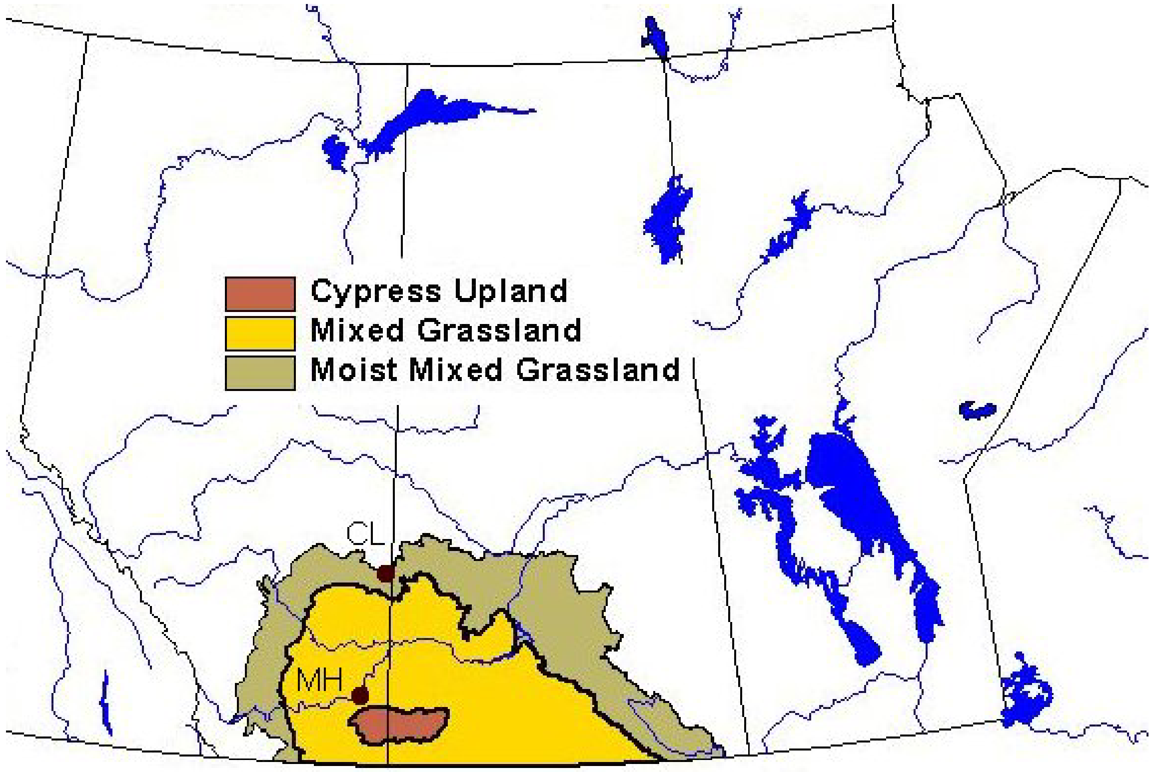

***Figure 1**. The Prairie Provinces and the ecoregions that presently correspond to the subhumid climate mapped in Figure 3. Chauvin Lake (CL) is the source of the paleosalinity data presented in this paper. The tree ring chronology from the Cypress Hills (Upland) was calibrated using instrumental climate data from Medicine Hat (MH).*

dry subhumid areas resulting mainly from adverse human impact" (Middleton and Thomas, 1992). We estimated PET from the widely used Thornthwaite formula (Dunne and Leopold, 1978), which uses temperature as the sole measure of the energy available for evapotranspiration. Monthly PET calculated must be adjusted using a correction factor for daylength according to latitude and month. We used Thornthwaite PET because it works best in mid-latitude continental climates where air temperature is strongly correlated with net radiation and because more complex formulas require net radiation and wind data which are available for few stations in the Prairie Provinces.

To map recent and future aridity we first loaded a gridded database of historical climate observations into a geographic information system (GIS). This database of mean monthly temperature and total precipitation was derived from all of the available monthly climate data in the Canadian Climate Archive for the Prairie Provinces and the surrounding climate regions. An interpolation procedure was used to calculate aridity at each intersection on a 50 km grid. These values should be viewed as representative of the region within 25 km of the grid point, although the gridded analysis cannot reproduce the high spatial variability associated with precipitation events. Further information on the database and interpolation procedure is available at http://www.cics.uvic.ca/climate/data.htm. Because mapping the aridity index on a 50 km grid produced jagged boundaries between categories of aridity (e.g. dry subhumid), the aridity data were was further interpolated to a 5 km grid to smooth the boundaries between maps units. The map units were defined using the legend in Figure 2.

Scenarios of future climate change were applied to the 50 km grid of baseline (1961-1990) temperature and precipitation to produce maps of future aridity centered on the 2020s, 2050s and 2080s. The Intergovernmental Panel on Climate Change strongly recommends the use of more than one GCM for any assessment of climate impacts. They also recommend that the selected GCMs show a range of changes in the key climate variables for the study region. In a recent study of climate change impacts on the island forests of the northern Great Plains, Henderson *et al*. (2002) thoroughly analyzed the available GCM scenarios and chose three that captured the range of annual temperature and precipitation changes projected for the region. Given the very similar scenario requirements of this recent study and the forecasting of future aridity attempted here, we accepted the conclusions reached by Henderson *et al*. (2002) and used the same climate change experiments. They are listed in Table 1. HadCM3 B21 forecasts the least increase in

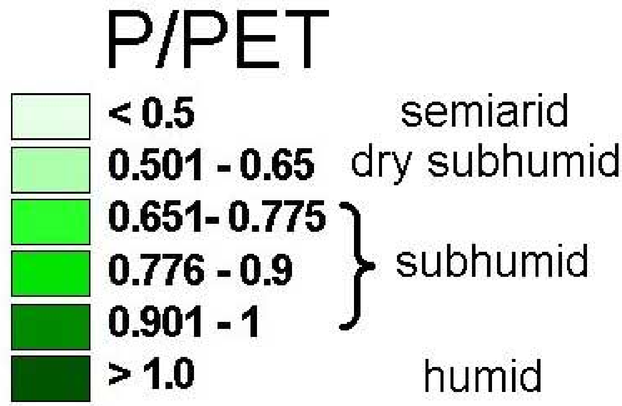

Figure 2. *A legend for mapping aridity according to the standard classification of the aridity index (Middleton and Thomas, 1992).*

temperature and greatest increase in precipitation. CGCM2 A21 forecasts the smallest change in precipitation and the largest increase in temperature. CSIROMk2b B11 is a mid-range scenario.

RECONSTRUCTING PAST ARIDITY

We derived detailed records of past aridity from lake sediments and tree rings. The tree rings are from lodgepole pine (*Pinus contorta*) in the Cypress Hills of southwestern Saskatchewan and southeastern Alberta (Figure 1). Standard procedures (Cook and Kairiukstis, 1990) were used to process the tree cores and disks, measure ring width to within .001 mm, assign the correct calendar year to each tree ring, and derive standardized ring widths (a residual index chronology) from the raw ring-width data. The reconstruction of June-July (P/PET) was based on the significant statistical relationship ($r = 0.452$; $p < 0.05$) between standardized residual ring width and P/PET for Medicine Hat, Alberta for the period 1900-1999. A tree-ring model of June-July aridity was calibrated using the first half of the instrumental climate record and validated by comparing predicted and observed aridity for the other half of the climate record. Then the calibration/validation periods were reversed and the model was calibrated and validated again. The final predictive model was calibrated using the full length of the instrumental record.

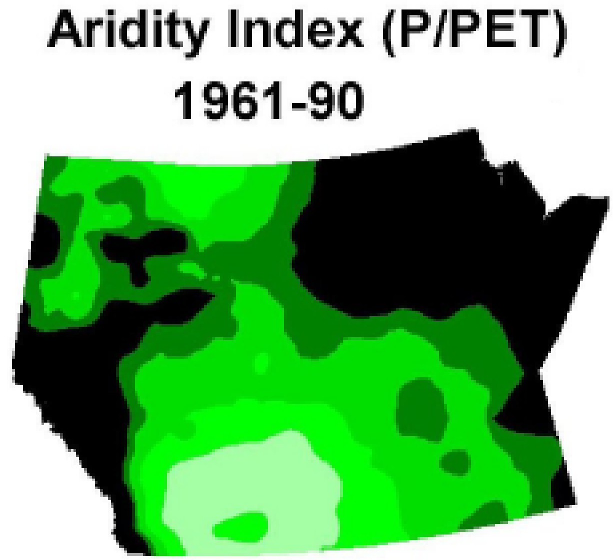

Figure 3. *Aridity map for the Prairie Provinces for the "normal period" 1961-1990. The most arid region is the dry subhumid ($0.5 \le P/PET < 0.65$) landscape of southwestern Saskatchewan and southeastern Alberta. Near the geographic centre of this region is the moist subhumid Cypress Hills.*

The analysis of aerial photographs shows that the size of small prairie lakes varies with historical changes in precipitation. As climate warms or dries, lakes become more chemically concentrated, leading to marked changes in the aquatic biota. Analysis of past changes in lake water chemistry demonstrates that salinity accurately records the occurrence of major drought events (Laird et al. 1996), with elevated salinity representing the dry conditions.

Table 1. The climate change experiments (from Henderson *et al*., 2002) used for the forecasting of future aridity.

Modelling Centre	Model	Emission Scenario[1]
U.K. Hadley Centre for Climate Prediction and Research	HadCM3	A21
Canadian Centre for Climate Modelling and Analysis	CGCM2	B21
Australian Commonwealth Scientific and Industrial Research Organization	CSIROMk2b	B11

[1] Special Report on Emission Scenarios (SRES) emission scenarios (Nakicenovic, 2000).

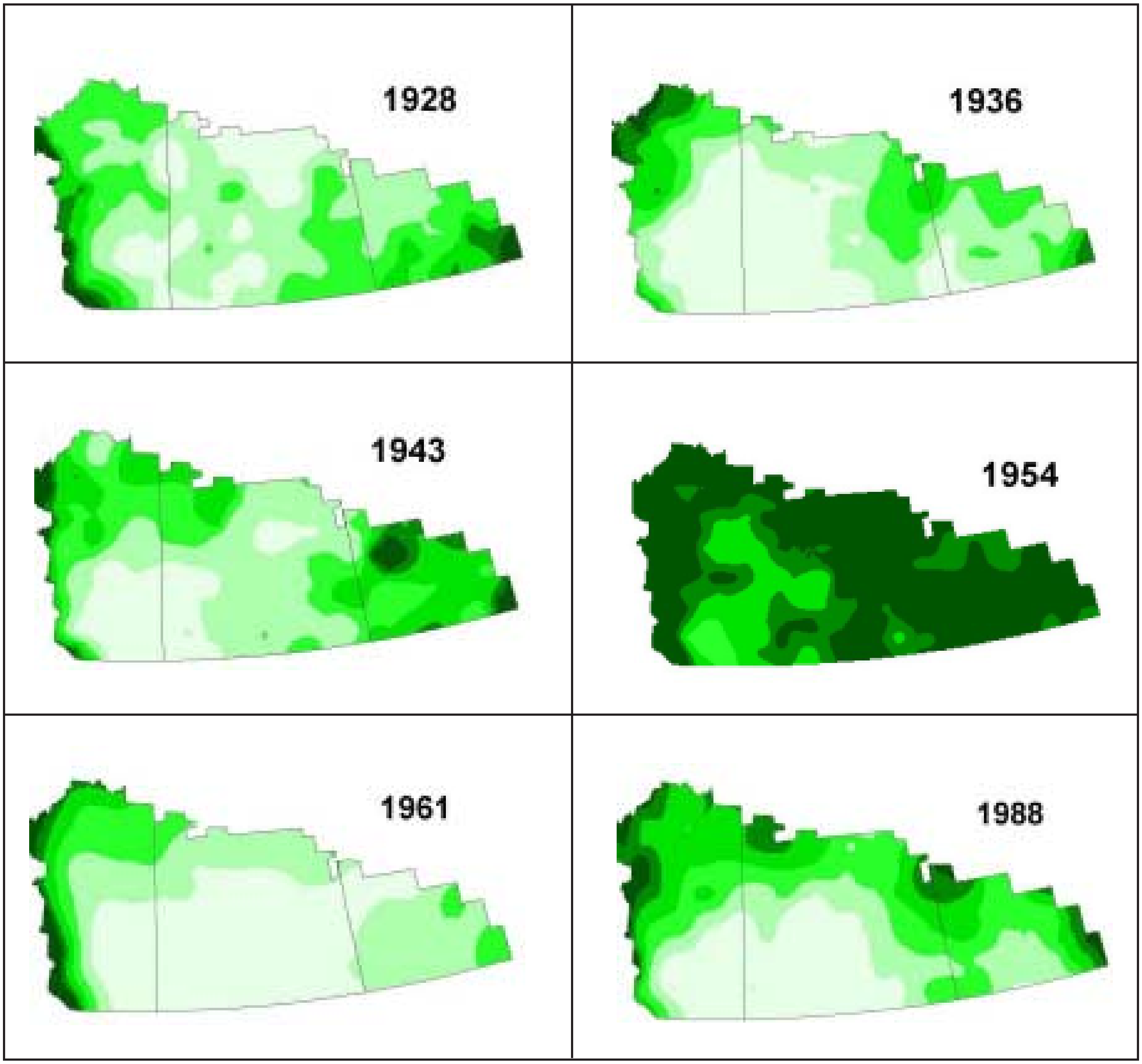

Figure 4. *Annual aridity for five drought years and for 1954 across the agricultural zone of the Prairie Provinces. During the drought years, the aridity index was < 0.5 (semiarid) over a large part of the agricultural zone. The most extensive drought was in 1961. The humid conditions of 1954, demonstrate that in some years the Prairies do not classify as dry lands except over small areas.*

Lake sediments cores were collected from Chauvin Lake, Alberta (Figure 1) using standard piston-coring procedures and sediments were cut into 2.5 mm intervals equivalent to an average of 1-3 years of lake history. Fossil diatoms were isolated, identified to species and quantified for alternate sediment levels, and changes in species composition were used in published inference models (Wilson *et al*. 1996) to reconstruct past changes in lake water salinity at intervals of 3-5 years. Sediment age was determined by analysis of naturally-occurring radioisotopes in recent bulk sediments (^{210}Pb) and individual plant macrofossils (AMS ^{14}C). Diatom-inferred changes in lake salinity were compared to instrumental climate records from 1910 to 1990 to evaluate the ability of fossil reconstructions to infer changes in aridity. PET data were filtered using three-year running mean to match the temporal resolution of the fossil time series. All time series were detrended by linear regression, and residual curves compared using correlation analysis. Lags of 1-5 years are applied to fossil data to evaluate the possibility of delayed hydrologic response to climatic forcing functions.

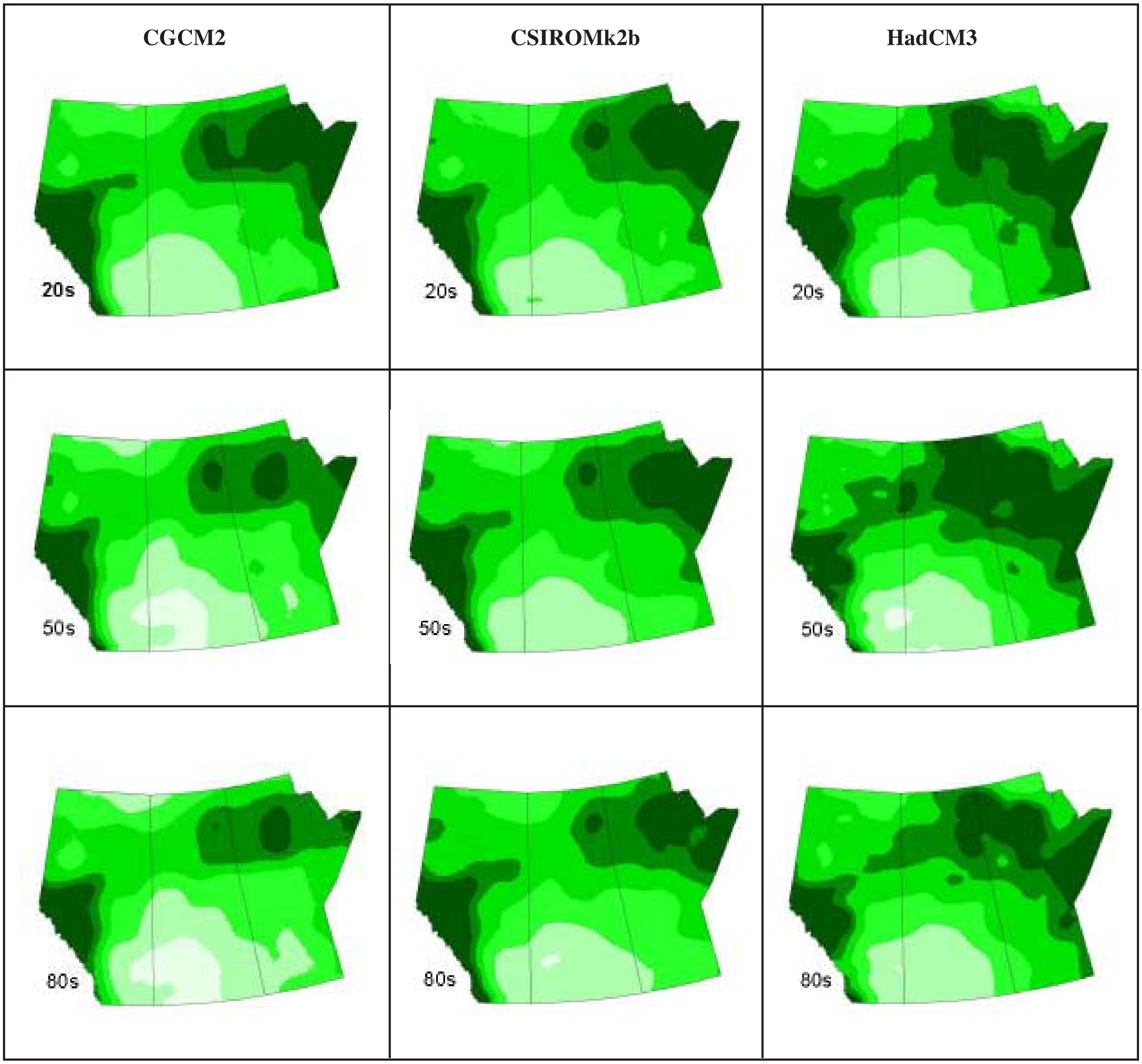

Figure 5. Aridity scenarios for the 2020s, 2050s and 2080s based on forecasts of precipitation and temperature from the Canadian (CGCM2), Australian (CSIROMk2b), and UK Hadley Centre (HadCM3) global climate models. These GCM experiments represent warm-dry, mid-range, and cool-wet scenarios, respectively.

FUTURE TRENDS

Future climate is expressed as change relative to a baseline climate. A map of baseline (i.e. 1961-1990) aridity for the Prairie Provinces (Figure 3) illustrates that, at 50 km resolution, the "normal" climate of the Prairie Provinces cannot be described as semiarid anywhere (P/PET < 0.5), even though this terminology is often used to describe the southern Prairies. The driest region, the dry subhumid (0.5 < P/PET < 0.65) landscape of southwestern Saskatchewan and southeastern Alberta, corresponds to the mixed grass prairie ecoregion. An analysis of the longest instrumental record (Medicine Hat, AB) in this area shows that annual P/PET varied from 0.34 (1943) to 1.24 (1927), with 26 years of semiarid conditions (AI < 0.5). On average, these dry events occurred approximately every fifth year, although only eight semiarid years were seen after 1950.

With the large variation in annual climate at each location, there is corresponding variation in the geographic extent of aridity from year to year. Each historical drought

Windmill for drawing water, southwestern Saskatchewan

had a unique geographic extent and intensity, although semiarid conditions were consistently recorded in southeastern Alberta and southwestern Saskatchewan (Figure 4). The "normal" dry subhumid climate of this region reflects the relative high frequency of below average precipitation and low P/PET. The most extensive drought was in 1961. The humid conditions of 1954 demonstrate that in some years the prairies do not classify as dry lands (P/PET < 0.65) except over small areas.

Scenarios of future aridity centered on the 2020s, 2050s and 2080s are mapped for the Prairie Provinces in Figure 5 for the CGCM2 A21 (warm-dry), CSIROMk2b B11 (mid-range), HadCM3 B21 (cool-wet) climate change scenarios. Under the CGCM2 A21 scenario, a small area characterized by a semiarid climate (P/PET < 0.5) appears in western Saskatchewan by the 2020s and expands significantly by the 2050s. In contrast, forecasts using the CSIROMk2b B11 mid-range scenario suggest that perpetually semiarid conditions will be evident only by 2080, although a dry subhumid climate will extend into southwestern Manitoba. The HadCM3 B21 scenario indicates the least climate change, with a marginal increase in the area of subhumid climate and maximum aridity in mid century. Taken together, these forecasts suggest a general increase in the geographic extent of dry conditions, with possible risks of desertification in the more extreme scenarios (CGCM2 A21).

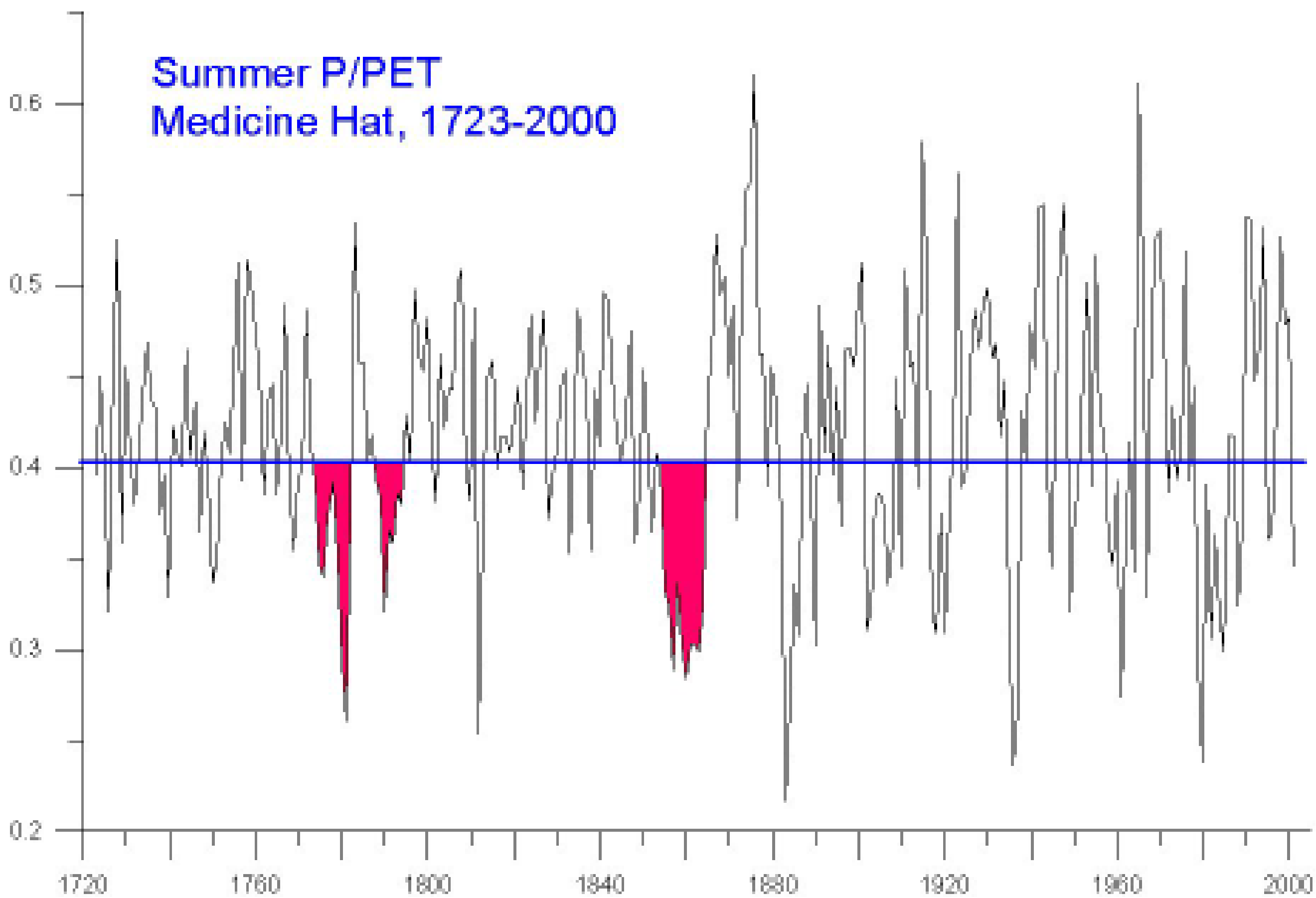

Figure 6. Proxy summer aridity for Medicine Hat, Alberta as reconstructed from residual index tree ring chronology from Pinus contorta *from the Cypress Hills. The red fill highlights prolonged summer droughts of the 18th and 19th centuries.*

PAST VARIABILITY

The reconstruction of summer aridity for 1723-2000 (Figure 6) revealed that events of high aridity occurred regularly during the past 3 centuries, with major droughts indicated for 1768-1782 and the 1786-1796 and 1851-1864. The aridity (P/PET) signal in the tree rings mostly reflects variability in precipitation, because Thornthwaite PET is a function of temperature and heat has both positive and negative affects on tree growth, depending on air temperature and soil moisture conditions. Not only is the response to precipitation direct and unambiguous, but amounts of rain and snow are much more variable from year to year than mean temperature and in turn evapotranspiration.

Wheatfield, southern Alberta

In this proxy aridity record, the mean interannual variance (as standard deviation) was greater during the instrumental period (post-1884; SD = 0.080) than in the preceding period (1723-1883; SD = 0.063). This prominent increase in inter-annual variability may be related to a mid 19th century shift in the Pacific Decadal Oscillation (D'Arrigo *et al.*, 2001). The consecutive years of summer aridity highlighted in Figure 6 are further evidence of prolonged aridity prior to Euro-Canadian settlement of the western Canadian plains and the instrumental observation of climate. The impacts of these

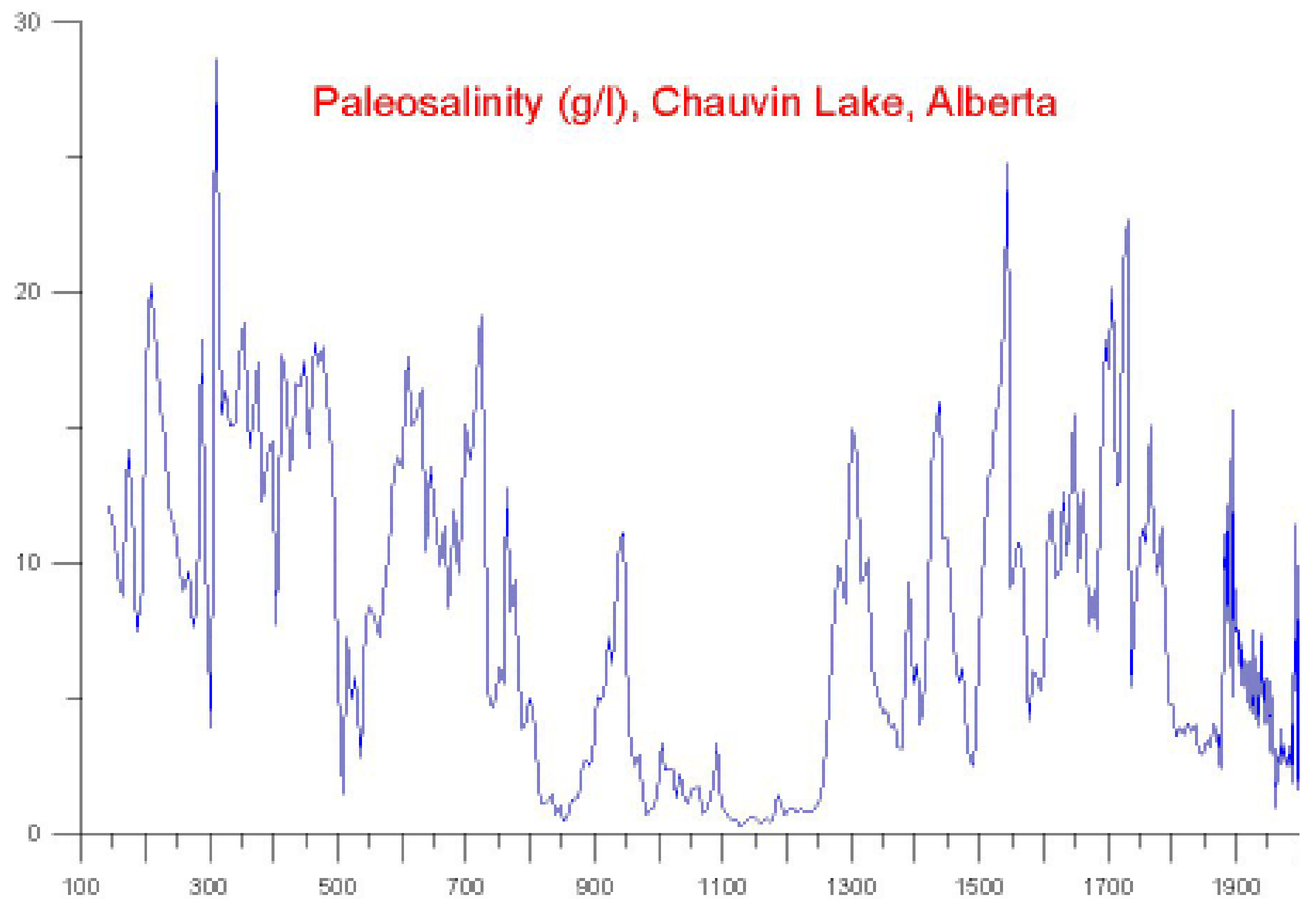

Figure 7. *Diatom-inferred paleosalinity for Chauvin Lake, Alberta for the past two millennia. High salinity corresponds to high aridity. The lowest salinity since the mid 1300's was during the 1950s to 1980s.*

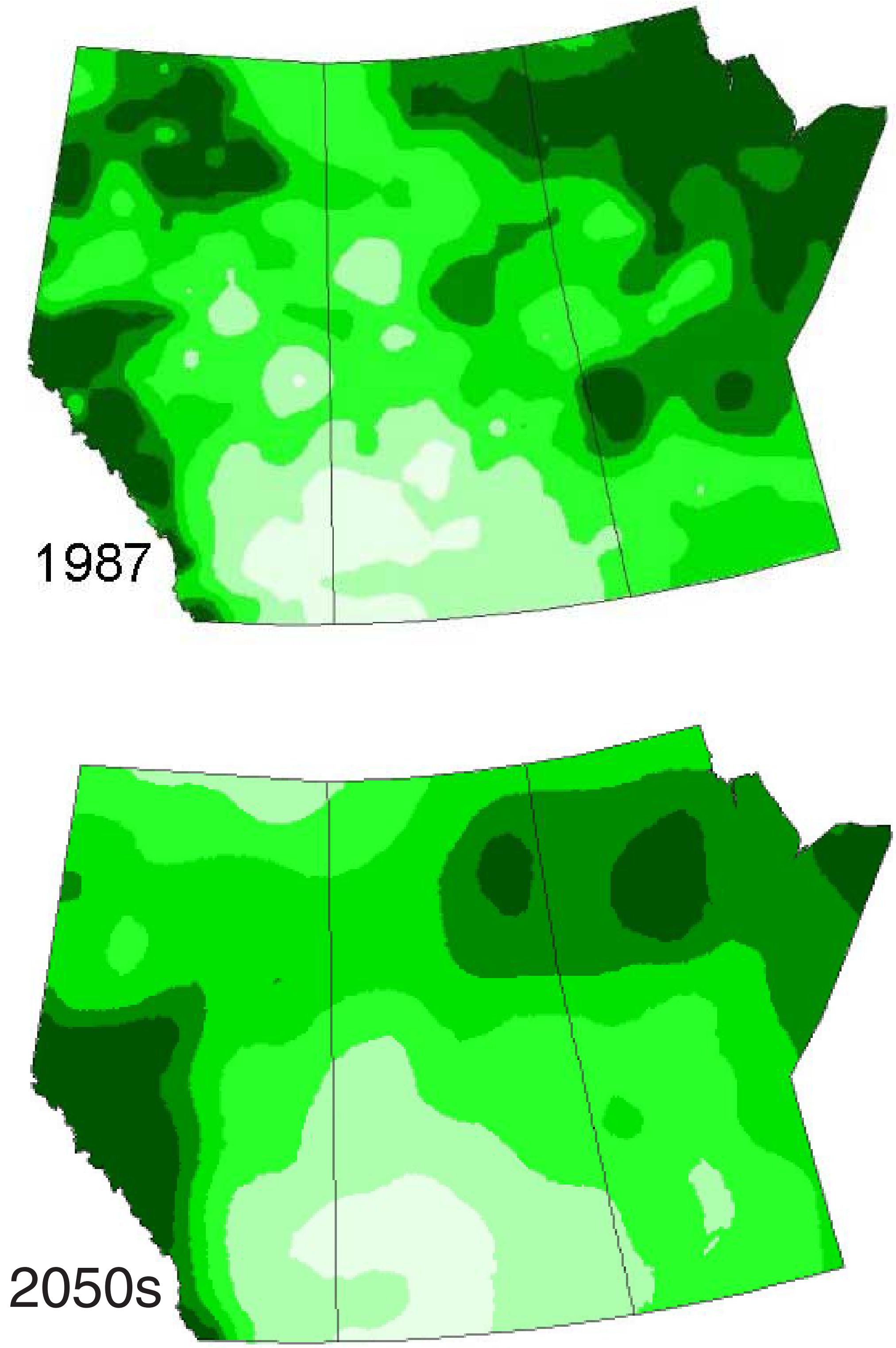

Figure 8. *P/PET in 1987 and forecasted for the 2050s, showing that a dry year like 1987 can serve as an analogue of the extent of semiarid and dry subhumid climate expected by the 2050s under a warm and dry climate change scenario (CGCM2 A21).*

droughts are described in Wolfe *et al*. (2001). Their relevance here is as possible analogues of anomalous precipitation expected with global warming in contrast to the climate of the 20th century, and particularly 1961-1990, the basis for our definition of the normal climate.

Paleoclimatic reconstructions based on the 2000-year salinity record from Chauvin Lake, AB, also suggest that past drought severity was greater than that recorded during the instrumental period. Detrended lake salinity data, inferred from the fossil diatoms, was significantly ($p < 0.05$) and positively correlated with PET during 1910-1990. Correlations were also positive and significant at lags of one or two years. Using these observations, and the drought of 1988-89 as a benchmark, analysis of past salinities reveals that climatic conditions were continuously dry during the 4th to 8th centuries and regularly arid during 1300-1750 (Figure 7). Severe events were also recorded during 1860-1890, an interval of broadscale droughts in central North America. Salinities declined substantially during the 20th century, reaching values during the 1960s and 1970s that were the lowest of the past 750 years.

IMPLICATIONS FOR SOIL, WATER AND VEGETATION MANAGEMENT

Analysis of climate normals (1961-1990) reveals that a large part of the southern Canadian Plains usually has a dry subhumid climate, although P/PET was rarely < 0.5 (semiarid) when analyzed on a 50x50 km grid. There is a high degree of spatial variability such that any given site could experience a wide range of climate, from semiarid (P/PET< 0.5) to humid conditions (> 1.0). Such high variability is also evident on longer timescales, as recorded both from tree-ring (Figure 6) and lake sediment (Figure 7) reconstructions. These same records demonstrate that more prolonged, intensely arid events were common in the past. The modern climate normals (1961-90) are not representative of the full range of potential climatic conditions, even in the absence of global warming.

The increasing aridity projected by the GCM scenarios represents a higher frequency of dry years over a larger area. As a result of an increase in mean annual temperature and, in turn, potential evapotranspiration, with even the coolest and wettest climate change scenario, there is a marginal increase in the area of subhumid climate in the Prairie Provinces by the 2080s. The Canadian GCM forecasts the least increase in precipitation and the largest increase in temperature and therefore an approximately 50% increase in the area of subhumid climate and a significant area of semiarid climate by the 2050s. Past droughts may provide important benchmarks to evaluate potential impacts of increasing aridity forecast by GCMs. For example, comparison of climatic conditions observed in the pre-drought year 1987 shows a marked similarity to the average conditions forecast by the CGCM2 A21 scenario for 2050, in terms of the geographic extent of semiarid and dry subhumid climate (Figure 8). Dry conditions during 1987 are viewed as partly responsible for establishing more extensive droughts during 1988-1989 (Figure 4) and suggest that future increases in aridity may produce conditions that favour the regular development of large-scale droughts.

The implication of more frequent and widespread droughts is that they place a larger area at risk of crop failure, water shortages and desertification more often unless there are counteracting management strategies. The critical variable will be the duration of the semiarid conditions in any given area. The scenario of increased climate extremes includes unusually wet years during which social and biophysical systems will recover from drought. If aridity is prolonged, however, the resistance of systems could drop below critical thresholds, such that they will not recover during the next wet year.

Drought adaptation strategies must acknowledge the potential for prolonged drought. Improved drought risk management supports effective responses to impending drought, reducing the cost of drought over the long term through planning and preparedness. This contrasts with the costly and untimely short-term solutions that result from the ad hoc response to an existing drought crisis. A policy framework to minimize the adverse impacts of drought and increasing aridity under climate change must support adaptation of soil and water management practices to climatic variability that exceeds the experience from the non-aboriginal history of the Canadian plains.

Our analysis of climatic proxies suggests that the climate of the 20th century was anomalous in terms of the absence of sustained drought. Furthermore, comparison of instrumental records and climatic reconstructions suggests that the climate normal period of 1961-1990 may have been among the most benign of the past 750 years. Possibly, the climate of the period 1921-1950 is more characteristic of the past and future climate of the Prairie Provinces than the "normal" climate of 1961-1990. Because both lake and tree-ring analyses recorded an abrupt amelioration of climatic conditions at near the start of the instrumental record, we suggest that the immediate impacts of future global warming may be to return the prairie environment to past conditions in which persistent aridity was recorded for intervals of decades or longer.

Killdeer badlands, Grasslands National Park

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PHOTO CREDIT

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