1. **Grantee:** Peter R. Leavitt (PIN 107767), Limnology Laboratory, Department of Biology, University of Regina, Regina, SK, S4S 0A2.
2. **Title:** Sustainable Agriculture in Western Canada: Planning for Droughts Using the Past (STP 0201967).
3. **Co-investigator:** Gemai Chen (PIN 163409), formerly Department of Mathematics and Statistics, University of Regina, Regina, SK, S4S 0A2; now Department of Statistics, University of Manitoba, Winnipeg, MB, R3T 2N2.
4. **Budget:**

	Requested	Awarded	Spent
Year 1	$96,127	$96,127	$96,127
Year 2	$89,667	$89,667	$89,667
Year 3	$92,310	$92,310	$92,310

5. **Amount remaining as of 31 March 2001:** $0
6. **Achievements:**

Objectives:

1. Reconstruct changes in salinity of three prairie lakes at 1-3 year intervals over the past 800 years.
2. Calibrate inferred lakewater salinity with common indices of drought severity using 50-100 years of local instrumental climate and agricultural data.
3. Quantify the frequency, intensity and duration of drought during the past 800 years in each prairie province.
4. Determine relationships among paleoclimatic reconstructions in each province to estimate the geographic extent of past droughts.
5. Document how drought occurrence impacts water quality.
6. Develop predictive models to estimate drought occurrence during the next 5-50 years.
7. Incorporate future drought probabilities into actuarial calculations for determination of crop insurance premiums.
8. Publish a summary monograph on the history and future of droughts in western Canada.

Milestones and Achievements:

In Nov 1997, we were awarded a three-year strategic grant to develop novel paleoecological and statistical techniques to predict the intensity, duration and frequency of droughts on the Canadian Prairies. This report summarizes our main results and conclusions. Further project details are available on our website **http://www.uregina.ca/drought.**

Surveys were conducted in spring 1998 and 1999 to evaluate lake suitability for climatic reconstructions. First, candidate lakes were identified from aerial photographs that demonstrated lake-level change in response to known climatic events. Second, short cores were obtained from over 50 lakes, sectioned in 1-cm intervals, and analyzed for preservation of fossil diatoms, evidence of historical changes in salinity, and congruence of saline taxa with known climatic events (e.g., droughts of 1930s, 1980s). Humboldt Lake SK (52°08.5'N, 105°06.48'W), Chauvin Lake AB (52°41.41'N, 110°06.02'W) and Nora Lake MB (50°28.30'N, 99°56.19'W) satisfied these criteria and were selected for full analyses. Finally, 1.75-m cores encompassing 2000 years were obtained from each study lake in 1998-99 and were sectioned in 2.5 mm intervals (<5 year resolution). Radiometric analysis of ^{210}Pb (10 dates/core; Flett Research Ltd, MB) and ^{14}C activities (2-6 dates/core; IsoTrace Ltd, ON) demonstrated that all long cores exhibited high temporal resolution (~4 yr) and minimal mixing, a fact confirmed by the presence of fine laminations in most sections of all cores. In addition to our three main sites, we developed collaborations with scientists at Queen's University that allowed us to add drought predictions at Oro Lake SK (49°47'N, 105°21'W) and Moon Lake ND (46°51'27"N, 98°09'30"W). The latter results are complete and are also presented below.

Space limitations do not allow us to describe all our new data and modelling in great detail. Briefly, our drought prediction analyses clearly demonstrate that modern risk assessment models do not adequately capture the true frequency, duration and intensity of past droughts. Further, we suggest that present adaptive strategies and insurance models greatly underestimate future drought risks, especially considering the accelerating effects of global warming on drought occurrence. As detailed below, our analyses show that the probability of economically-significant droughts (i.e., losses >$75billion/yr) occurring by 2030 AD is at least 22% in MB and SK, and that risks rise to ~40% in AB and ND. Canadian droughts all exhibited cycles characteristic of potential lunar (14-18 y), solar (20-25 y) and oceanic (60-75 y) forcing mechanisms, whereas flood events had pronounced 25, 50 and 300 year cycles. Critically, our analyses show clearly that 20th century climate was comparatively benign and that past conditions were much more severe than those experienced during the modern agricultural era. For example, the 'dust bowl' of the 1930s was one of the mildest droughts of the past 2000 yr; most droughts were both more severe and longer-lasting, with an average duration of over 10 years. Together, these patterns demonstrate that catastrophic droughts are a natural, regular feature of the Prairie environment and have the capacity to seriously disrupt Canadian economy and society. Below we detail our data and interpretations, evaluate the implications of our analyses for the Prairies, and suggest possible adaptive strategies.

Drought measurement and fossil calibration: During round-table discussions in our first drought workshop (11 Sept 1998; *see below*), we were asked by our user sector to identify what type of drought was reconstructed from paleoclimatic records (ie., agricultural, hydrologic, precipitation, fire, etc.) and to demonstrate that fossil records were statistically related to long-term historical data. To address these questions, we compared reconstructions of past lake salinity and fossil community composition to direct historical measurements of climate and agricultural production at all sites.

Canonical Correspondence Analysis (CCA) was used to compare temporal trends in fossil diatom and historical data during the 20th century. For analyses at Moon Lake ND, fossil data included diatom species composition and diatom-inferred (DI) lake water salinity (1891-1980). Climate data included the Rooy Drought Index (RDI), Bhalme-Mooley Drought Index (BMDI) and precipitation data (1893-1980). Crop insurance and agricultural (wheat) production data included drought-related indemnities (1948-1980), wheat production (acres planted, harvested, yield per acre, total production; 1889-1980), and crop failure ([harvested-planted]/planted; 1919-1980). Climate and crop data were smoothed using a 3-yr running mean to approximate fossil resolution (2.7 yr), while fossil species abundances were square-root transformed prior to analysis.

CCA indicated that three historical variables were significantly correlated to past diatom species composition. Taken together, wheat yield per acre, total crop production and crop failure explained 32% of past variations in diatom community composition, clearly indicating that paleoclimatic reconstructions were recording drought impacts on agricultural production. Monte Carlo testing demonstrated that each variable explained an independent and significant portion of the variance in past community composition. Linear regression also showed that DI-salinity is significantly correlated with crop failure ($r=0.45$, $P<0.05$). Finally, CCA identified a weak correlation ($P=0.09$) between mean BMDI (May-Oct) and paleoclimate data.

Similar analyses at Humboldt Lake SK showed even stronger correlations, with 64.8% of fossil variance explained by changes in crop production (flax, spring wheat) and climate (annual evaporation, cumulative departure from mean precipitation, standardized precipitation index, Palmer Drought Severity Index) between 1938-1998 (Fig. 1). As at Moon Lake, crop production was strongly and negatively correlated ($r = -0.54$) to diatom-inferred lake salinity. At Chauvin Lake AB, over 28% of diatom community change (1938-1998) was explained by historical variance in spring wheat production, cumulative departure from mean precipitation, and annual evaporation, whereas crop production (oats, barley) and annual precipitation explained 29.2% of fossil variance at Nora Lake MB (1965-1999). Together, the strong correlations between modern climate, crop production and reconstructed lake conditions demonstrate that drought risk assessments based on fossil diatoms are particularly relevant to the Prairie agricultural sector and should accurately record the major changes in climate that influence production of economically-important crops.

Comparisons of historical and fossil records also allowed us to evaluate the impacts of human land-use practices on lake chemistry and hydrology. In addition to the diatom and pigment analyses proposed originally, we also analysed all core samples for stable isotope content (δ^{15}N, δ^{13}C) using research supported by grants from the Canada Foundation for Innovation (CFI; $775,000; Leavitt PI) and BIOCAP Canada ($49,000; Leavitt PI). Sedimentary δ^{15}N content is an excellent indicator of N inputs to lakes from sewage and land use. Comparison of δ^{15}N with fossil diatoms and pigments demonstrated that while humans did influence Humboldt (Fig. 2) and Moon lake chemistry after 1940, these changes did not influence climatic reconstructions: salinity remained the principle environmental factor explaining diatom community variation. There was little evidence of human impacts at either Chauvin or Nora lakes.

Risk Assessment using Paleoclimate records: Having demonstrated that paleoclimate data record agriculturally-relevant droughts (*objective 2* above), we developed and applied new methods of risk assessment to better quantify the probability of future prairie droughts (*objectives 3 and 6*). Our analytical procedures were developed first using the 2000-yr paleoclimate record from Moon Lake ND, then were applied to our new sites in AB, SK and MB.

Analytical details: Paleoecological reconstructions demonstrated that there has been a natural decline in the salinity of Moon Lake over the past 2 millennia. Because we were interested mainly in the temporal behaviour of extreme events (high salinity; droughts), this natural trend was subtracted from the reconstructed salinities in the subsequent analysis (Fig. 3). Once detrended in this way, positive values of DI-salinity indicated above-average salinities, whereas negative values indicated below-average salinity levels.

In order to quantify past drought behaviours and accurately assess future drought probabilities, we first had to establish our definition of a drought. Based on discussions with our user group, *we defined past droughts as any event in which DI-salinity exceeded the value recorded for Moon Lake in 1988-89, the last regional drought.* North American agricultural losses exceeded $75 billlion in 1988-89. This critical level was equivalent to 1.4 times the standard deviation (1.4xSD) of all positive, detrended salinity values, and was used as a benchmark measure of drought occurrence at all our Canadian sites. Thus in our analysis, a drought was any event in which observed DI-salinity (s_i) exceeded the critical threshold (s_t) of 1.4xSD of positive detrended values. Each drought was considered to have a beginning time (b_i), and ending time (e_i) and a duration ($d_i = e_i - b_i$). These values were calculated for each drought event, allowing us to estimate the number of droughts (n) during the past 2000 years that were as or more severe than the 1988 drought (s_t). Our protocol also allowed us to estimate the average duration of such droughts, as

$$^1/_n \sum_{i=1}^{n} d_i$$

Probabilities of future droughts were estimated by describing the past drought behaviour using a Weibull model, then calculating the conditional probabilities of future droughts. To estimate such a probability, we first calculated the time between every two adjacent droughts ($x_i = b_{i+1} - e_i$; $i = 1, 2 \ldots n-1$). When these inter-arrival times are small, droughts occur frequently, whereas if inter-arrival times are large, droughts are rare.

To describe past drought behaviour, we modelled inter-arrival times using the Weibull distribution, a standard industrial reliability model whose probability density function is given by

$$f(x;\alpha,\beta) = (\beta/\alpha)(x/\alpha)^{\beta-1} \exp\{-(x/\alpha)^{\beta}\},\ 0 < x, 0 < \alpha, 0 < \beta.$$

In this formulation, x denotes inter-arrival time, α is the scale parameter and β is the shape parameter. Recent statistical research suggests that for a high threshold salinity s_t, the beginnings and ends of droughts (b_1, e_1,..., b_n, e_n) can be described by a Poisson process, thus inter-arrival times (x_i) are approximately exponential random variables. Since the Weibull distribution contains the exponential distribution as a special case (when $\beta = 1$), the use of the Weibull distribution is justified. Further, the Weibull model provided a better fit to observed data than did the Pareto distribution. In all cases, the maximum likelihood method was used to estimate the Weibull scale parameter α (as α) and the shape parameter β (as β).

The probability of having a drought as or more severe than that of 1988 by the future year y was calculated using a conditional probability analysis. In this procedure, the condition is that there has been no drought during the length of time since 1989 ($y_o = 10$ yr in 1999). Thus the probability of a future drought as or more severe than that of 1988 is

$$P(X \le y \,|\, X \ge y_0) = \frac{\exp\{-(y_0/\hat{\alpha})^{\beta}\} - \exp\{-(y/\hat{\alpha})^{\beta}\}}{\exp\{-(y_0/\hat{\alpha})^{\beta}\}},$$

where X is a random variable which gives rise to the inter-arrival times x_i's, and y is greater than y_0. Using this model, the risk of droughts can be calculated for any year y in the future. For each site, probabilities were estimated also for a family of critical salinities (and hence drought severities) representing 5% percentile intervals from 50% to 95% (ie., s_t = 50th, 55th, 60th….95th percentile of positive detrended salinities).

Similar procedures were used to quantify the risk of low salinities arising from episodes of extremely high water availability (herein termed ‘floods’ for ease of reporting). In this case, *floods were defined as lake water salinities below that recorded during the 1911 flood of the Red River ND*, a site adjacent to the Moon Lake drainage basin. Detrended salinities measured during this event were 1.4 times the standard deviation of all negative detrended salinities in Moon Lake and provide a critical benchmark of equivalent magnitude to that used in our definition of droughts. This critical minimum was used at all sites to facilitate geographic comparisons.

Monte Carlo simulations were used to quantify 95% confidence limits (95%CL) of both drought and flood probabilities at each site. In this procedure, the sequence of observed inter-arrival times was randomized 10,000 times, and new probabilities of a critical event (s_t = 1.4xSD) were calculated for each of the next 30 yr, for each permutation. For a given future year, the 0.975th and 0.025th quantile of the 10,000 predictions constitute the upper and lower 95%CL.

One of the main concerns identified in our second user workshop (Oct 1999) was whether droughts or floods exhibited significant cycles during the past 2000 yr. Identification of cycles is critical for user-sector planning and adaptation, as well as for identifying potential forcing functions (e.g., El Niño-Southern Oscillation [ENSO], 3-7 yr; Pacific Decadal Oscillation [PDO], ~65 yr). Normally, such spectral analysis would not be possible because fossil time series are often non-stationary. Further, even if a significant period were identified, it is often difficult to determine which portion(s) of the entire time series contribute to the cycles (e.g., droughts, floods, central tendencies). Fortunately, we were able to circumvent both problems using a novel combination of *data censoring* and standard spectral analysis of time series. In our approach, all salinities (s_i) less than the critical threshold (s_t) were replaced by the critical value itself. These censored time series were then studied using standard Fourier analyses for the presence of significant cycles in extreme values, but not for the presence of specific cycles. Tests with different critical values demonstrated that the analysis was insensitive to the precise critical threshold used, but confirmed that as s_t increased towards an intermediate optimum, the time series approached a stationary condition, as required for Fourier spectral analysis.

Finally, two approaches were used to evaluate the potential impacts of future global warming on our risk assessments. First, because global temperatures have risen since the end of the 19th century, we compared drought probabilities calculated in 2000 using complete (0-2000 AD) and truncated (0-1900 AD) time series to determine whether on-going warming is evident in our records. Second, because future warming may increase drought frequency beyond the range of historical observations, we compared standard risk assessments with those calculated from 2000-yr time series in which 5 droughts were added statistically between 1850 and 1997. This later case represents a drought occurrence during the past 150 yr that is three-fold greater than past maximum frequencies, and is larger than that predicted to occur in the future.

<u>*Results from Moon Lake ND*</u>:

Conditional probability analysis of paleoclimate data from North Dakota suggested that the probability of a drought as or more severe than that of 1988 is only 1.9% in 2001 AD (Fig. 4). However, this probability rises to 23.3% by 2015 AD and 39.7% by 2030 AD, with a 95% confidence that the true value lies between 29.5 and 54.0% by 2030 AD. Over the past 2000 years, there have been 29 such droughts, with an average duration of 5.5 yr (range 1-31 yr) and an average inter-arrival time of 63.4 yr (Table 1). Spectral analysis confirmed the presence of significant cycles within the censored time series, and visual inspection suggested major drought periods of 63 and 158 years (Fig. 5). Smaller peaks corresponded to 45, 26, 23, 18 and 15 yr. Our analyses also demonstrated that drought occurrence has been greater since 1900 than before, and that including the past 100 years data increased the probability of future droughts by 1.9% by 2030 AD. Similarly, the addition of 5 droughts during the past 150 yr increased drought probability by an additional 1.7% in 2030 AD. Analysis of patterns with differing drought intensity revealed that the 1988-89 drought was only in the 70th percentile of drought severity and had similar probabilities of occurrence (39.7%) as milder events (50th %ile; 46.9%). Statistically, droughts were possible in any given year, and even very extreme events (95th %ile) still had an 11.1% chance of occurring by 2030 AD. Finally, we determined that the probability of more economically-damaging, multiple-year droughts was ~50% that of single year events, and that 'double droughts' of 1988 magnitude had ~19% probability of occurring by 2030 AD.

Conditional probability analyses were also used to model flood probabilities for the Red River drainage basin, where 1997 flood losses exceeded $850 million US dollars. Moon Lake lies in the Red River drainage and would be expected to be subject to dilution (and low salinity events) due to exceptional snow pack melt and spring rainfall, the main causes of flooding. Estimates of flood probability were based on the observation that the last major freshening event occurred in 1832, and that 165 years had elapsed by 1997. Weibull models were fitted to the Moon Lake time series using the 1832 freshening as our definition of a critical flood and future probabilities were calculated using our conditional probability procedures. Results indicated that the probability of a flood event the magnitude of that in 1832 was 75% by 1997.

Using our standard definition of a flood (1.4xSD), our model also estimated that flood probability was 55.1% by 2030 AD, with 95%CL of 41.5-78.5% (Fig. 4). Importantly, such high probabilities occur despite the fact that our standard flood is in the 95th %ile of past flood intensities (ie., most others are less intense), and suggests that extreme floods are a common feature in the Red River basin. Consistent with this, 39 floods were recorded in the past 2000 years, with a mean inter-arrival time of 39.5 yr (±43.4 yr). Addition or removal of 5 floods in the past 150 yr altered probabilities only 3%. Interestingly, spectral analysis of censored flood data identified the same 63 yr period as occurred for droughts, inferring a common forcing mechanism. Other spectral peaks included 105, 39, 20 and 8 yr cycles, although these could not be tested for individual statistical significance.

Chauvin Lake AB:

Drought risk was higher at Chauvin Lake AB than at any other prairie site (Fig. 4). The probability of standard drought (1.4xSD) occurring by 2030 AD was 44.9%, with a 95%CL of 32.6-66.5%, a mean inter-arrival time of 60.5 yr and an average duration of nearly 12 years (Table 1). Pronounced 100 and 300 year cycles were evident in spectral analyses, although 33, 25, 14 and 9 yr periods also may have been present. Unexpectedly, droughts of the 1930s were among the mildest on record, with most events being either more severe or of longer duration. Of considerable concern is the observation that the most severe droughts of the past 2000 yr (95th %ile) have an 18% probability of recurring by 2030 AD. As a consequence of this naturally-high occurrence, risk of future droughts increased only 1% in response to a tripling of the drought frequency during 1850-2000.

Floods were uncommon in eastern Alberta, resulting in low risks (22.7%) and high uncertainties (95%CL 5.2-41.5%) of future occurrence for standard events (1.4xSD; 95th%ile). As a result, flood probabilities varied more substantially (±5% in 2030) than at other sites in response to changes in future flood frequency. Only 12 standard floods occurred in the past 2 millennia, with an average interarrival time of 111 yr, but a duration of 40 yr suggesting that wet intervals could be prolonged. Spectral analysis of censored time series was significant, with cycles of 147 and 295 yr.

Humboldt Lake SK:

Future drought risk was substantially lower in central Saskatchewan than in Alberta or ND, with a 22.9% (14.0-51.9% 95%CL) probability of occurrence by 2030 AD (Fig. 4). Droughts were comparatively uncommon (11 total; 117 yr inter-arrival time) but tended to be of long duration (average 13 yr). As in Alberta, Fourier analyses demonstrated significant periodicity, with apparent cycles of 302, 101, 43, 30, 22 and 18 yr duration. Similarly, Humboldt Lake analyses demonstrated that 20th century climate was unusually benign with no major droughts on record, including the 1930s (Fig. 3). In contrast, paleoclimate reconstructions showed that severe droughts were common prior to 1900 AD, with the most substantial drought occurring during the 1890s. In addition, regional climate appeared to be uniformly more arid before ca. 800 AD. As a result, future global warming might be expected to have a pronounced impact in central SK. Consistent with this view is the observation that the addition of 5 droughts during 1850-2000 raised drought risks 5.6% by 2030 AD, the greatest value of any prairie site.

Overall, future flood probability in central SK (48.1%; 95%CL 31.7-67.8%) was similar to those of ND and MB (*see below*) and was twice that of AB by 2030 AD. Although mean inter-arrival times were shorter (56.8 yr) than in the west, censored time series had similar spectral peaks (155, 309 yr) and mean event duration (22.2 yr). However, unlike all other sites, flood events also had very strong 25 yr cycles in Saskatchewan (Fig. 5), suggesting multiple climatic causes.

Nora Lake MB:

Reconstructed climate in southwestern Manitoba was dramatically different from that at other prairie locations through much of the past 2000 yr (Fig. 3). In general, Nora Lake was characterized by naturally low salinities (high water availability), infrequent droughts (8 total, 161.1 yr inter-arrival time) and short event duration (5.3 yr). Risk assessment showed that the probability of standard drought was relatively low (29.7%), but that forecast confidence was also low (95%CL 8.0-56.6%) because droughts exhibited categorical occurrence (present/absent) rather than a continuous range of intensity (Fig. 3). Consequently, impacts of global warming were easily detected at this site, with a 5.4% increase in drought probability observed as a result of 3-fold increased drought frequency 1850-2000. Spectral analysis of censored data showed no significant periodicity. Eastern Manitoba was also unique in that the latter half of the 20th century (1965-present) was characterized by some of the driest conditions of the past 2000 yr, suggesting that farm flooding in 1999 may be more characteristic of the region than was previously believed. Overall, these patterns suggest that southwestern Manitoba was the least drought-prone of prairie sites.

Flood probabilities were high (51.5% by 2030 AD; 95%CL=41.5-78.5%) and inter-arrival times low (40.8 yr) at Nora Lake, similar to results from North Dakota (55.1%, 39.5 yr). However, unlike Moon Lake, mean duration was much longer in Manitoba (39.6 yr vs. 8.6 yr). As at other Canadian Prairie sites, spectral analyses of censored flood data revealed significant periodicity, with apparent cycles of 62, 151 and 302 yr. Flood probability analysis was moderately sensitive (±3%) to changes in flood frequency during 1850-2000.

Constraints to Adaptation: Water Quality vs. Quantity

Successful adaptation to future droughts requires clear understanding how surface water quality and availability will change during extreme events (*objective 5*). As originally proposed, we used fossil pigment analyses to quantify changes in the abundance of both total algae and potentially-toxic colonial cyanobacteria (blue-green algae) in response to droughts. At all sites, we found only weak evidence for a correlation between total algal production and lakewater salinity (r^2=0.03), suggesting that while water potability may decline during droughts, there will be little need to process surface waters for excess algae. Instead, we find standing waters may have to be treated to remove cyanobacterial toxins. In particular, we found a strong correlation between the concentration of biomarkers from potentially-toxic N-fixing cyanobacteria (e.g., *Aphanizomenon, Anabaena*) and lakewater salinity (r^2=0.35; $P<0.0001$), particularly in central Alberta and Saskatchewan (Fig. 6). There was little relationship between past salinity and water quality in western Manitoba.

Changes in lake level were also reconstructed independently from analyses of fossil diatoms to evaluate how water quantity might vary in response to droughts. At Humboldt Lake, inferred modern depth (6.3 m) agreed closely with direct measurement (6.7 m) and historical changes estimated from aerial photographs (*see website*). Our analyses further suggested that regional water levels were at a historical maximum and that present availability is two-fold greater than at any other point in the past 2000 yr (Fig. 7). In contrast, modern water levels in AB and MB are within the range of past observations, suggesting that regional variability in water availability may be a critical factor regulating the success of adaptation efforts.

Synthesis and Conclusions:

Our analyses show clearly that severe droughts are a natural feature of the Prairie environment. Strong correlations between reconstructed lake chemistry and crop production during the 20th century (r^2 = 0.28-0.65; P<0.05) demonstrated that risk forecasts based on fossil records are directly relevant to the Prairie agricultural sector. Extreme droughts (e.g., 1930s and worse) occur every 60-100 yr, with a 23-45% probability of occurring by 2030. Most historical droughts have been longer-lasting (~10 yr) and more intense than those of the 1930s, and most exhibit some periodicity. For example, droughts in western Canada have 14, 22, 30, and 100 yr cycles, whereas floods have 25,50, and 100 yr cycles. However, we caution that these cycles cannot be tested individually for statistical significance, and explain relatively little of the total variance in past drought behaviour. Instead, we note that drought occurrence is best described by probabilities of occurrence, rather than deterministic prediction based on cycles. Overall, droughts have been most common in eastern Alberta, whereas floods occur regularly in all areas except Alberta. Future climatic warming may increase drought likelihood. However, given the highly variable nature of drought occurrence, risk of future occurrence will change little over the next 30 years. *This does **not** mean that global warming is unimportant; it means that the impacts of global warming will be difficult to detect for the next 30 yr because of naturally high variability in drought occurrence.*

Widespread droughts were common in SK, AB and ND during 0-750 AD and 1300-1900 AD, but were less frequent during the 20th century than during the previous 1900 yr. In contrast, the past 35 years were relatively dry in western Manitoba. Overall, our analyses suggest that surface water availability was much as two-fold greater now than in the past two millennia. Return to previous low water availability will significantly reduce water habitats (e.g., for waterfowl breeding) and will limit our ability to adapt to droughts using storage technologies. Further, the quality of standing water will likely diminish during droughts due to increased blooms of potentially-toxic cyanobacteria. Land-use and sewage treatment practices may interact with future droughts to further degrade water quality.

Implications and Recommendations:

The Canadian Prairies are a natural environmental, social and economic unit in which a high proportion of economy (~40%) is reliant on the agricultural sector. Within this sector, the single largest source of economic losses during the past 40 yr has been crop failure due to water shortages. Given that our analyses suggest that there have been no major droughts in western Canada during this period, we feel that our analyses and recommendations apply beyond the agricultural and insurance sectors. Specifically, we conclude:

1. Comparison of drought patterns among sites showed that while coherent, prairie-wide events can occur (e.g., 1890s), drought intensity and timing often varies with geographic location (*objective 4)*. Consequently, we recommend the use of network adaptation strategies, including inter-provincial crop insurance agencies that disperse risk over a broader geographic and economic base, yet remain within the natural climatic and environmental zone. Similarly, we see a continued need for governmental agencies, such as the Prairie Farm Rehabilitation Agency, to develop adaptative strategies specifically for the Prairies.
2. The presence of common drought and flood cycles among Canadian sites suggest continental-scale causal mechanisms. Cycle periods indicate lunar (14-18 yr), solar (20-25 yr), PDO (60-75 yr) and other (300 yr) participation in droughts. Although ENSO signals (4-7 yr) were not pronounced, these cycles were near the limits of our analytical resolution. As well, similar geographic gradients of drought risk and modern climate (ie., dry in west, wetter in east) suggest that basic climate controls have been stable through the past 2000 yr. Together, these observations suggest that mechanistic models (e.g., regional GCMs) might use our paleoclimatic data as climate change scenarios. If deterministic models can replicate past climates, they may provide significant predictive value for forecasting droughts.
3. The 20th century climate was benign. Global warming may return the Prairies to past, higher drought frequencies. Severe droughts of the 18th and 19th centuries may be the best models for expected impacts of future droughts on Prairie agriculture and water availability.
4. Drought onset is usually rapid and may prevent effective *ad hoc* adaptation to prolonged events. Past droughts have lasted up to 40 years. Increased use of preventative measures and reduced reliance on Federal relief programs is recommended.
5. Past droughts have diminished both the quantity and quality of surface waters. Consequently, adaptive strategies that rely on surface water storage may prove ineffective. As suggested by our user sector, future studies are required to evaluate the potential for use of groundwater as a drought-breaking measure. Regular reliance on irrigation is not recommended in order to avoid severe aquifer depletion, as is occurring presently in the central USA.
6. Despite high probabilities of future droughts (up to 45% by 2030 AD), risk assessments may be conservative because of both the location of lakes near the periphery of the prairies, and because of potential impacts of global warming. Expansion of our paleoclimate approach to a network of sites within the prairies and across prairie-woodland ecotones is recommended.

7. Training of Research Personnel:

Name	Position (yr)	Responsibility
Dr. O. Olson[1]	PDF 98-99	Diatom analyses, field manager, climate statistics
Dr. S. Wunsam	PDF 99-00	Diatom analyses
Dr. M. Chen	PDF 98-00	Time series statistics, probability estimates
Dr. J. Rusak	PDF 99-00	Climatic analyses, environmental/social impacts
Mr. M. Graham[2]	Tech 97-00	Core collection, field & pigment analyses
Mr. J. Hovdebo[2]	Tech 98-99	Core collection, field & diatom preparation
Ms. T. Ivanochko[3]	Tech 98	Website development, field work
Mr. J. You	PhD 98-00	Time series modelling
Mr. L. Zhang	PhD 98-00	Time series modelling

[1] Dr. Olson (PhD Minnesota) has accepted employment as a private statistical consultant in Madison WI, USA. Dr. Wunsam (PhD Austrian Academy of Sciences) completed all diatom analyses and Dr. Rusak (PhD York) has conducted the climatic reconstructions in association with Dr. Brian Cumming (Queen's University); [2]half-time positions, remaining funds provided by U. Regina, contracts, or grants; [3]Presently MSc. Paleoclimatology (UBC).

8. Accessability of Results to Supporting Organizations:

User Sector

Organization	Contact	Organization	Contact
Agriculture & Agri-food Canada -	Sean McGinn	Manitoba Crop Insurance Corp. -	Doug Wilcox
Alberta Agric. Financial Services –	Tom Crozier	Manitoba Hydro -	Bill Girling
Alberta Agriculture and Food -	Len Kryzanowski	Prairie Farm Rehab. Admin.-	Ted O'Brien
Canadian Wheat Board -	Bruce Burnett	Sask Agriculture and Food -	Cameron Wilk
Canadian Wildlife Service -	Bob Clark	Sask Crop Insurance Corp. -	John Kiss
Ducks Unlimited (IWWR) -	Henry Murkin	Sask Environment Res. Manage. -	Syd Barber

Environment Canada (AES) - Ross Herrington
Geological Survey of Canada - Don Lemmen
Heritage Parks Canada - Pat Rousseau
Canadian Plains Res. Centre – Dave Gauthier
Sask Grazing & Pasture Tech. -Z. Abouguendia
Sask Research Council - Elaine Wheaton
Sask Water Corp. - Alex Banga
Sask Wetlands Corp. – Greg Riemer

Communication

Close contact has been maintained with our user groups throughout this project. Particularly frequent communication has been achieved with scientists and managers from the SK Crop Insurance Corp, Environment Canada (AES), Agriculture and Agri-Food Canada (PFRA), SK Water Corp, and SK Agriculture and Food. All members of the user sector have also received newsletters, electronic correspondence, and have access to our dedicated website at **http://www.uregina.ca/drought**. This site is updated regularly with our activities, progress, and latest research findings and will be maintained for at least 1 year after project completion.

As originally proposed, we have used a series of three workshops at University of Regina to present our results, solicit advice on adapting our findings to user needs, and identify additional research directions. Each workshop included invited presentations on climate change and agriculture (by SK Crop Insurance, AES, AAFC), formal presentations on project progress, and roundtable discussions of project goals, results and progress. We feel strongly that these forums were ideally suited to the NSERC Strategic program and highly recommend them to other projects. For example, our second workshop was invaluable for identifying user concerns about possible human impacts on paleoclimate records. As a consequence, Leavitt wrote an additional grant to CFI to establish the Environmental Quality Analysis Laboratory. New isotope-ratio mass spectrometry instrumentation obtained via that grant allowed us to develop metrics of human impact on lakes (see above), a significant technology with applications beyond drought forecasting. Similarly, user interest in the cyclic nature of climatic extremes lead directly to the development of our unique censored spectral analysis. In addition, the direct personal contact resulting from these workshops greatly facilitated data exchange with our users. Our workshops proved valuable for dissemination of our results to the public, as members of the print (*Western Producer*, *Leader Post*) and television media (*CTV*-Regina) were present at, and reported on, the first and third workshops. Finally, individual workshops were held with SK Crop Insurance to harmonize risk assessment methodologies.

Significant efforts were made to present our risk assessment analyses to national and international conferences. Papers were presented at 16 conferences, including the American Society of Limnology and Oceanography, Society of Canadian Limnologists, Ecological Society of America, North American Long-range Weather and Crop Forecasting Workshop, Crop Insurance Research Managers Conference, International Symposium on Paleolimnology, Agriculture and Greenhouse Gas/Climate Change Workshop, Canadian Water Resource Association Conference, North American Lake Management Society, Agri-Food Innovation Fund Sustainable Agriculture Conference, Geological Society of America, and Canadian Association of Geographers. In addition, we were invited to make research and management presentations to 16 international organizations, including NASA, US EPA, Institute for Ecosystems Studies, Great Lakes Environmental Research Laboratory, Duke University, University of Washington, University of Stockholm, University of Umeä (Sweden), University of Arizona, Université de Montreal, North Dakota State University, Université de Quebec á Montreal, and University of Manitoba. Full details of these presentations are available on our project website.

Because of the importance of climate change to Western Canada, our research has been the subject of intense regional interest by television, radio and print media. These reports include: 1) Print articles in the *National Post* (Mar 2001), Edmonton *Journal* (Mar 2001), Calgary *Herald* (Mar 2001), *Western Producer* (Oct 1998), Regina *Leader Post* (Nov 1997, Mar 1999, Mar 2001 [x2]), Regina *Free Press* (Nov 1997), *Agri-View* (in *Western Producer*; June 1998), Agriculture and Agri-Food Canada *Innovation Report* (Winter 2000), Humboldt *Journal* (Aug 1998), and the University of Regina *Third Degree* (Fall 1997); 2) Television reports on *CTV* Regina (Sept 1998; Mar 1999), *CBC TV* Regina (Apr 1999), *Radio Canada* Regina (July 2000) and *Global TV* Regina (Apr 1998, Mar 1999, Mar 2001), and; 3) Radio interviews on *CBC* Calgary (Mar 2001), *CBC* Alberta (Mar 2000), *CBC* Winnipeg (Sept 1999, Apr 2000), *CBC* Regina (Nov 1997, Sept 1998, Mar 2000 [x2]), *CJME* Regina (Mar 2001), *CJOB* Winnipeg (Mar 2001), and *QR Radio* Calgary (Nov 1997).

Ongoing Collaborations:

Several publications are now being prepared based on data presented here and in our professional presentations. In addition, all students involved with the project will be submitting theses. These works will be collected upon completion and published as a single volume for distribution among our user sector (*objective 8*). Editorial costs of this volume are provided by the Canadian Plains Research Centre as part of the original partnership agreement of this grant. Because of the requirement for formal peer review, we anticipate this volume will be published during 2003.

We are also continuing our collaboration with the crop insurance industry in order to determine the best means for incorporating our risk assessments into actuarial calculations (*objective 7*). In addition to presenting our results to the Crop Insurance Research Managers Conference in 1999, we plan to present our analysis to the federal actuarial program for formal evaluation. Because the probabilities of future droughts estimated here are considerably greater than those used in traditional assessments, we anticipate some difficulty in incorporating our results into actuarial models. We will be working with our user sector to resolve this issue. In addition, MB Hydro and PFRA have expressed interest in expanding our approach to larger geographic scale, including boreal environments adjoining the prairies. Finally, as mentioned above, we have obtained additional funding from BIOCAP Canada to analyze our cores for C, N and stable isotope content in order to quantify the impact of past droughts on the carbon sequestration potential of prairie lakes. Although lakes and wetlands occupy only ~7% of land area, they may represent as much as 50% of the total C storage capacity of the Prairies, and may be essential to meeting Canada's commitments to reducing net greenhouse gas emissions.

9. Benefits to Canada and Non-academic Participating Organizations:

Our analyses are already being used by partner agencies to re-evaluate their drought risk assessments. For example, as a direct consequence of this project, Manitoba Hydro is reconsidering the use of the 1930s as a benchmark of critical drought intensity (B. Girling, MB Hydro, pers. comm.). Similarly, PFRA issued a 'briefing note' to their Minister in Ottawa to better inform senior planning officials of drought likelihoods, particularly in Alberta. As well, our participation in the Long-term Weather and Crop Forecasting Workshop in Regina attracted national media attention on the high potential for severe drought in Alberta (*National Post*; 19 March 2001).

Accurate estimates of drought likelihoods are essential for a stable economy and sound resource management in western Canada. Our analyses show that present risk assessments are inadequate and suggest that adaptation strategies must account for greater actual risks. Our conclusions and data should be particularly relevant to reinsurance companies that use catastrophe prediction to spread risks over a larger economic base. Similarly, Federal agencies should use these improved risk assessments to evaluate the adequacies of present adaptation strategies. When combined with developing long-range climate forecasting models, improved drought prediction will ultimately aid long-range planning by grain marketing and transportation companies, resulting in lower costs to producers and the general public. Improved drought predictions will also improve the efficiency of lake and reservoir management, increase economic flexibility, and ultimately reduce costs to the public. Overall, the project provides predictive environmental technologies that will ultimately benefit farmers and crop insurance corporations, drought relief agencies, agricultural agencies, and power generation sectors.

Figure Legends: (see text for discussion)

Fig. 1. CCA of fossil diatom communities and significant explanatory variables for Chauvin Lake, Alberta. Data demonstrate that fossil data record agricultural droughts.

Fig. 2. Changes in diatom-inferred salinity, lake production and N flux (as $\delta^{15}N$) at Humboldt Lake, SK, during 1800-2000. Patterns show that land-use practices disrupted N cycling and lake production, but only after major changes in salinity had already occurred (ca. 1940).

Fig. 3. Historical changes in detrended DI-salinity over the past 2000 yr in Chauvin Lake AB, Humboldt Lake SK, Nora Lake MB, and Moon Lake ND. Positive values indicate greater than average aridity (droughts), negative values indicate humid climates (floods). Horizontal line represents 0 g/L detrended salinity.

Fig. 4. Conditional probability of occurrence of critical droughts (top) and floods (bottom) in Chauvin (C), Humboldt (H), Nora (N) and Moon (M) lakes by 2030 AD.

Fig. 5. Censored Fourier spectral analysis for Chauvin (C), Humboldt (H), Nora (N) and Moon (M) lake drought (top) and flood (bottom) time series.

Fig. 6. Relation between fossil pigments from cyanobacteria and past lake salinity at Humboldt Lake.

Fig. 7. Historical changes in diatom-inferred water level of Humboldt Lake SK, 1000-2000 AD. Horizontal line = 1997 lake level (6.7 m).

Table 1. Summary statistics for prairie droughts (top) and floods (bottom).