RESPONDING TO GLOBAL CLIMATE CHANGE IN THE PRAIRIES

Volume III of the Canada Country Study: Climate Impacts and Adaptation

Ross Herrington
Brian Johnson
Fraser Hunter

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This report has been published by the Adaptation and Impacts Section, Atmospheric Environment Branch, Environment Canada, Prairie and Northern Region.

Further copies can be obtained from:

Environment Canada
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Environment Canada
phone: 1-800-668-6767
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Canadian Cataloguing in Publication Data

Herrington, Ross

Responding to global climate change in the Prairies:
Volume III of the Canada Country Study: climate
impacts and adaptation

ISBN 0-662-25921-1
Cat. No. En56-119/1-1997E
Includes bibliographic references.

1. Climatic changes – Prairie Provinces – Forecasting
I. Johnson, Brian N.
II. Hunter, Fraser G.
III. Canada. Environment Canada.
IV. Title
V. Title: Volume III of the Canada Country Study: climate
impacts and adaptation

QC981.8C5H47 1997 551.69711 C97-980311-X

This is a component report of the Canada Country Study: Climate Impacts and Adaptation. In addition to a number of summary documents, the first phase of the Canada Country Study will produce six regional volumes, one volume comprising twelve national sectoral reports, and one volume comprising eight cross-cutting issues papers. This is The Canada Country Study – Volume III: Prairies Regional Report.

For further information on the Canada Country Study (CCS), please contact the CCS national secretariat in Toronto at 416-739-4389 (telephone), 416-739-4297 (fax), or ccs.cia@cciw.ca (e-mail).

Ce rapport est une partie composante de L’Étude pan-canadienne sur les impacts et l’adaptation à la variabilité et au changement climatique. En plus de quelques documents sommaires, la première phase de L’Étude pan-canadienne produiront six tomes régionaux, un tome comprenant douze rapports nationaux au sujet des secteurs sociaux et économique, et un tome comprenant huit papiers concernant les questions intersectorielles. Ce rapport est L’Étude pan-canadienne – Tome VII: Rapport Regional pour les Prairies.

Pour plusieurs renseignements concernant L’Étude pan-canadienne (ÉPC), contactez le secrétariat national de l’ÉPC à 416-739-4436 (téléphone), 416-739-4297 (facs.), ou ccs.cia@cciw.ca (poste élect.).

EXECUTIVE SUMMARY

REGIONAL CLIMATE SENSITIVITIES

Drought is the most significant climatic characteristic of the Prairies. Many prairie residents recall the severe drought year of 1988, and some the 'dirty 30s'. However, postglacial proxy climate data indicate that the prairies have experienced intervals of high temperatures and abnormally low precipitation over the past 1000 years which were far more severe than during this century. The most severe drought of the past 500 years in the Prairies occurred between approximately 1791 and 1800. Historically, droughts have had a return period of 30 to 50 years; this has not changed appreciably.

Droughts have had significant impacts on the economy and on aquatic and wildlife resources of the Prairie Provinces. For example, during the 1930s drought, wheat yields declined 32 percent, 200 000 farms failed and 300 000 people migrated from the southern Prairies.

After the 1988 drought, crop insurance and special drought assistance paid out over $1.3 billion to prairie cattle producers and grain farmers, an amount also supplemented by provincial support programs. Despite this support, Manitoba showed net farm income losses of 50 percent and Saskatchewan 78 percent. Export losses from agriculture were estimated at $4 billion. Due to the effects of the drought, and previous years of low prices, an estimated 10 percent of farmers and farm workers left the agriculture sector in 1988.

The droughts of the 1980s extended northward into the northwest forest. Forest effects included reduced wood volume increments, higher than normal seedling mortalities, tent caterpillar and spruce budworm outbreaks and considerable fire damage and fire suppression costs. Disturbance areas greatly increased during the 1970s and 1980s as compared to the previous 50 years.

The 1988 drought affected the energy sector in Manitoba more than in either Saskatchewan or Alberta because of Manitoba's reliance on hydroelectricity. Manitoba experienced a 4 percent decrease in hydroelectric power generation compared to "normal" years, a 72.6 percent drop in export sales from 1986/87, and a net income loss of $26.4 million. In Saskatchewan, the proportion of thermal generation and the volume of energy imports increased due to the drought's effects. Purchased electricity costs increased by 28.9 percent and operational problems were encountered at thermal power stations.

In the insurance sector, the demand for farm "rain insurance" in the northern Great Plains of the United States rose sharply during the 1988 drought. The Federal Insurance Company lost $20 million and CHUBB Corporation lost $48 million in claims that year.

In many prairie basins, the demand for water often exceeds the firm supply. The lack of available water in 1988, for example, resulted in widespread deterioration in water quality and in an increase in the consumptive use of water. This led to an increase in government assistance programs. Evaporation rates from reservoirs and lakes have been abnormally high in recent decades.

Aquatic ecosystems are sensitive to changes in temperature, salinity, general water chemistry, and the frequency and intensity of floods and droughts. Southern wetlands have undergone considerable alteration in the last several decades, suffering from both human-induced and natural changes. Drought decreases above-ground plant biomass, and species diversity and richness, and may result in local extinction of many rare species. Waterfowl populations decreased during the dry 1980s and an increase in diseases, such as avian botulism, occurred.

IMPACTS OF CLIMATE CHANGE

Most climate change scenarios for the prairies show an increase in temperature and reductions in soil moisture with a doubling of atmospheric carbon dioxide. However, some models have shown a small increase in precipitation while others predict a small decrease. In addition, not all parts of the prairies will experience the same effects.

While most climate change scenarios suggest that the semi-arid regions of the prairies can expect an increase in the frequency of drought, some literature suggests that no major change in drought frequency is likely for southern Alberta.

Agriculture

Precipitation could be the limiting factor for agricultural production on the prairies based on the current models. The predicted increases in temperature would likely lengthen the growing season but higher temperatures and lower soil moisture may adversely affect dryland agriculture. Also, increased crop production may be possible in northern regions where suitable soils exist. The extra heat would likely increase the potential risk of insect infestation.

Given the potential changes in crop production variables, average potential yields may fall by 10-30 percent.

Forest Ecosystems

The boreal forest is the ecosystem that is expected to be affected the most by future climatic changes because of its high latitude location and because of its climatic sensitivities. In general, the circumpolar boreal forest is likely to decrease in area, biomass, and carbon stock, with a move toward younger age-classes and considerable disruption at its southern boundary. Growth and productivity could improve in central and northern regions, especially on favourable sites, and decrease in the south, especially with increased droughts. Disturbances such as fire, insects, and diseases could increase.

Energy

Electricity has the potential to be severely impacted by climate change. Thermal power stations become less efficient as reservoir water temperatures increase. Hydroelectric production will have to compete with a number of other uses, primarily agricultural, for the diminishing water supply. Increased demand for water pumping and summer cooling and a decreased winter demand could push electrical utilities into a summer peak load position. Possible reduced hydropower production caused by decreasing water flow could result in increasing thermal power production with an increase in fossil fuel consumption and greenhouse gas emissions.

Insurance

Smaller insurance companies and policy holders may be unable to afford the higher premiums which will accompany the higher risk. Underwriters may also be less willing to accept this risk. Crop insurance premiums may increase, or taxpayers may be expected to carry the increased costs.

Direct health effects of global warming may include increased mortality and illness due to expected increases in temperatures and duration of heat waves, and fewer cold-related deaths. Indirect health effects may include aggravated respiratory and allergic disorders.

Recreation and Tourism

Warmer temperatures will encourage algae and plant growth, which may lead to fish kills and reduced recreational fishing at many locations. This will also reduce the quality of other water-based activities such as swimming and water skiing. The drying up of potholes that is expected to accompany rising temperatures could lead to reduced production of waterfowl.

Water Supply and Demand

Predicted prairie runoff varies from below normal to above normal, depending on the GCM scenario selected. For example, some scenarios indicate an increase in the amount of average annual precipitation, a larger number of extremes in weather, greater frequency of severe storms, increased evaporation, decreased snowpack and an earlier disappearance of the prairie snowpack.

If the magnitude and frequency of extreme events increase, existing dams and other water control structures, which were designed on the basis of the magnitudes and flood frequencies of past extreme events, might be impacted.

Because of the warmer weather there will be a greater need for good quality drinking water for livestock, wildlife and humans. More conflicts will occur among users over the limited resource.

Natural Environment

Changes in the hydrologic cycle due to climatic change are likely to affect the availability and quality of critical fish habitat. Climate warming will have major consequences for some fish species since observed climate changes have already caused mid-summer water temperatures in many mid-latitude lakes to approach the thermal tolerance of a variety of these organisms. However, increasing temperatures will allow some freshwater fish species to extend their range into higher latitudes and may cause them to disappear from what is now the southern extent of their range.

Wildlife species tied to semi-permanent or seasonal wetlands are expected to be most affected by climate change in this region.

ADAPTATION TO CLIMATE

Agriculture

During the past century, farmers, particularly in areas where extreme soil moisture deficits are common, have adapted to climate by irrigating their crops. While this has been an effective adaptation strategy in the past, this technique may become less attractive if water supplies become more uncertain. Converting to more drought-tolerant crops provides another adaptation option in some areas. Also, farmers and livestock operators have begun to diversify into specialty crops (e.g. mustard seed, dry peas and lentils) and native species such as buffalo and elk.

Although the agricultural sector is able to respond and adapt to changes in climate, governments will play a role in how the sector adapts and how quickly. Current shifts in agriculture policy are starting to allow more flexibility in production, not only in techniques, but also in products.

Forest Ecosystems

Adaptive and mitigative strategies include managing stands and landscapes to reduce the likelihood of crown fires and large area fires, managing forest fuel, prescribed burning, preserving and enhancing biodiversity, and managing forest landscapes that are becoming increasingly fragmented.

The forest products industry can adapt to ecosystem changes by salvaging dying trees, replanting with better-adapted species, or moving to those places where timber becomes more abundant. However, adaptation for non-timber aspects, such as biological diversity, is more difficult.

Some possible “no regrets” adaptive actions include implementing uneven forest age management, maintaining an over-storey cover, managing for several species, and altering harvesting regimes to protect soils and maintain productivity. These actions attempt to mimic natural processes.

Energy

One of the adaptive strategies that could be employed by industry and individuals is mitigation through actions to reduce fossil energy consumption. This, in itself, will result in the need for the energy sector to adapt to changes in energy demand.

Many energy utility companies have adopted strategies to manage their ongoing operations to adapt to climate variability. Examples include: re-examining long range load forecasts; evaluating the suitability of thermal plants compared to hydoelectic plants in light of climatic change; and operational aspects such as research into the effects of icing on conductors and improvements in methods of calculating evaporative demands.

Insurance

Insurance companies adapt to losses by increasing premiums and/or deductibles, reducing or withdrawing coverage altogether, or by making the underwriting of risk conditional on certain actions being taken by the policy holder.

On more of a practical level, another possibility is to reduce investment in companies that contribute to greenhouse emissions. The industry is also lobbying for tighter building codes that improve energy efficiency.

Recreation and Tourism

Recreationists can adapt to climatic variability and change by traveling to alternative locations with more favourable conditions, reducing participation when conditions are unfavourable, or ceasing to participate in their usual activities. People also can undertake new activities or increase their involvement in other activities.

Water Supply and Demand

Large reservoirs (there are approximately 770 significant dams in the Prairie Provinces) have been constructed on virtually every major river system in the grasslands region. These reservoirs capture spring runoff for delivery during times of drought and reduce flooding during times of peak flows. Most of these reservoirs serve multiple objectives, such as for irrigation, power production, recreation, flood protection to downstream communities, and transfering water between drainage basins.

More than 110 000 farm and community dugouts have been constructed in the prairies to store spring runoff. Many rural areas rely on groundwater supplies, either entirely or as a supplement to surface water supplies. Regional water distribution systems are also becoming a common adaptation strategy.

Formal water management policies and legislation exist for international, interprovincial and provincial-territorial river systems which specify how much water can be used within each jurisdiction.

OPPORTUNITIES FOR FURTHER RESEARCH

While our knowledge of climate variability and change within the Prairie Provinces has expanded considerably over the past couple of decades, much research remains to be initiated. Some general research questions follow for each sector. Readers should refer to the respective appendices for further detail.

Agriculture

- Why do responses differ, and what characteristics of farming make certain types of regions more vulnerable or adaptive than others?
- What non-climatic conditions influence the propensity to adapt? What are the constraints on and incentives for adaptation in the future?
- How can agriculture become more sustainable in the event of climate change?

Forest Ecosystems

- What is the nature of the current interactions between climate and the boreal forest ecosystem? What critical monitoring needs are not being met?
- What is the net effect of changes in growth and changes in disturbances over the long and short terms?
- What changes in the economic importance of the forest resource can be expected with the types of climatic changes foreseen? How sensitive is the forest industry to these changes?

Energy

- What are the sensitivities of different parts of the energy sector to climatic change? How do these compare to the sensitivities of other sectors?
- What are the best quantitative and qualitative models for use in estimating impacts and testing adaptive strategies?
- What is the balance between adequate adaptation and mitigation? What are the linkages between adaptation and mitigation?

Insurance

- How can regional climate models be improved to assist insurance companies in setting fair and realistic premiums in the face of climate change?
- What kinds of risks can insurance companies expect when covering future climate-related damages on the prairies?

Recreation and Tourism

- What are the economic costs of creating favourable conditions for recreation?
- What resource conflicts exist due to competition for scarce resources, such as water? What legislation or other instruments can be developed to resolve these conflicts?

Water Supply and Demand

- How can regional climate models be improved to assess the impacts of climate change on water supply and demand? What is the potential for more extreme climate events?
- What socioeconomic impacts will exist in areas such as municipal water use, tourism and recreation, agriculture and power generation under a warmed climate?

Aquatic Ecosystems

- What are the linkages between climate change and the hydrologic cycle, and the chemical and biotic structure and functioning of aquatic ecosystems?
- How can short-term, intensive monitoring studies be integrated with existing past

environmental data and quantitative predictive models?

Wildlife and Biodiversity

- What are the synergistic effects of UV-B radiation, water chemistry, and agricultural chemicals on Canadian prairie amphibians?
- What are the possible impacts on wetlands under a changed climate?

RÉSUMÉ

SENSIBILITÉS DE LA RÉGION AU CLIMAT

La sécheresse est la première caractéristique climatique des Prairies. Nombre de résidants se souviennent de l'année 1988, particulièrement aride, et certains de la grande sécheresse des années 30. Cependant, les données climatologiques substitutives de l'époque postglaciaire révèlent que les Prairies ont connu, dans les 1000 dernières années, des épisodes de températures élevées et de précipitations anormalement basses qui ont été bien pires que ceux du présent siècle. La plus grande sécheresse des cinq derniers siècles a frappé les Prairies entre environ 1791 et 1800. Historiquement, ces épisodes ont une période de récurrence de 30 à 50 ans; c'est encore sensiblement le cas à notre époque.

Les sécheresses ont des incidences significatives sur l'économie des Prairies, ainsi que sur l'hydrologie et les espèces sauvages de la région. Par exemple, pendant la sécheresse des années 30, les rendements du blé ont baissé de 32 %, 200 000 exploitations agricoles ont fait faillite et 300 000 personnes ont dû quitter le sud de la région.

Après la sécheresse de 1988, les prestations d'assurance-récolte et les allocations spéciales de sécheresse versées aux éleveurs et aux producteurs de céréales des Prairies ont dépassé 1,3 milliard de dollars, montant que sont venus compléter des programmes d'aide provinciaux. Malgré cela, les pertes de revenu net des exploitations agricoles ont atteint 50 % au Manitoba, et 78 % en Saskatchewan. Les pertes du secteur agricole quant aux exportations ont été estimées à 4 milliards de dollars. Les effets de la sécheresse et les bas prix des années précédentes ont conduit environ 10 % des exploitants et travailleurs agricoles à quitter le secteur en 1988.

Les sécheresses des années 80 se sont étendues jusque dans la région forestière du nord-ouest. Les augmentations du volume de bois y ont été moindres et la mortalité des semis plus élevée que la normale; la région a en outre connu des infestations de livrée des forêts et de tordeuse des bourgeons de l'épinette, et le feu y a causé d'importants dommages, ce qui entraîné des coûts considérables de suppression des incendies. Pendant les années 70 et 80, les superficies affectées ont été beaucoup plus vastes que dans les 50 ans précédents.

Le secteur de l'énergie du Manitoba a été plus touché par la sécheresse de 1988 que ceux de la Saskatchewan ou de l'Alberta. En effet, la production d'hydroélectricité, dont cette province dépend plus que les deux autres, y a baissé de 4 % par rapport aux années « normales » et les ventes à l'exportation ont chuté de 72,6 % par rapport à 1986-1987, ce qui a entraîné une perte de revenu net de 26,4 millions de dollars. En Saskatchewan, il a fallu accroître la proportion d'énergie produite par des centrales thermiques, et le volume des importations d'énergie. Les coûts d'achat d'électricité ont monté de 28,9 % et les centrales thermiques ont connu des problèmes opérationnels.

Dans le secteur de l'assurance, la demande en « assurance-pluie » pour les exploitations agricoles a monté brutalement pendant la sécheresse de 1988 dans le nord des grandes plaines des États-Unis. Cette année-là, la Federal Insurance Company a perdu 20 millions de dollars en réclamations et la CHUBB Corporation Insurance Company 48 millions de dollars.

Dans nombre de bassins hydrographiques des Prairies, la demande en eau dépasse souvent l'approvisionnement ferme. La pénurie de 1988, par exemple, a entraîné une détérioration généralisée de la qualité de l'eau et une augmentation de ses utilisations avec prélèvement, qui ont à leur tour conduit à une augmentation des programmes d'aide gouvernementaux. Depuis quelques dizaines d'années, les taux d'évaporation des réservoirs et des lacs sont anormalement élevés.

Les écosystèmes aquatiques, quant à eux, sont sensibles aux changements de température, de salinité et de chimie générale de l'eau, ainsi qu'à la fréquence et à l'intensité des crues et des sécheresses. Au cours des dernières décennies, les milieux humides du sud ont subi une grave altération, due à des changements tant anthropiques que naturels. La sécheresse réduit la biomasse végétale au-dessus du sol, ainsi que la diversité et la richesse biologiques, et peut causer localement l'extinction de nombreuses espèces rares. Les populations d'oiseaux aquatiques ont baissé pendant les années 80, et on y a constaté une augmentation des maladies, comme le botulisme aviaire.

IMPACTS DU CHANGEMENT CLIMATIQUE

Selon la plupart des scénarios de changement climatique, un doublement du dioxyde de carbone atmosphérique entraînerait dans les Prairies une hausse de la température et des réductions de l'humidité du sol. Cependant, certains modèles ont suggéré une légère augmentation des précipitations, alors que d'autres en prévoient une faible baisse. En outre, les effets ne seront pas uniformes sur toute la région.

Bien que la plupart des scénarios de changement climatique laissent penser que les régions semi-arides des Prairies connaîtront probablement une fréquence accrue des sécheresses, certains études suggèrent que ce paramètre ne subira pas de changement important dans le sud de l'Alberta.

Agriculture

Les précipitations pourraient être le facteur limitant pour la production agricole dans les Prairies, si l'on en croit les modèles actuels. Le réchauffement prévu allongerait probablement la saison de croissance, et on pourrait voir une augmentation de production des cultures dans les régions du nord où les sols conviennent. Cependant, avec des températures plus élevées et une moindre humidité du sol, l'agriculture en terre sèche serait affectée. Le réchauffement risquerait aussi d'accroître le risque d'infestations d'insectes.

Vu les changements que pourraient subir les variables de production des cultures, les rendements moyens pourraient baisser de 10 à 30 %.

Écosystèmes forestiers

On pense que c'est l'écosystème de la forêt boréale qui sera le plus touché par les changements climatiques futurs, parce qu'il se situe à des latitudes élevées et qu'il est sensible au climat. En général, la forêt boréale circumpolaire devrait connaître une diminution de la superficie, de la biomasse et du stock de carbone, ainsi qu'un décalage vers les classes d'âge plus bas et des perturbations considérables à sa limite sud. La croissance et la productivité pourraient s'améliorer dans certaines parties privilégiées du centre et du nord, mais baisser dans le sud, surtout avec l'aggravation des sécheresses. Il pourrait y avoir une augmentation des perturbations telles que le feu, les insectes et les maladies.

Énergie

Le changement climatique pourrait avoir des incidences très profondes sur l'électricité. Les centrales thermiques perdent de l'efficacité à mesure que l'eau des réservoirs se réchauffe. La production hydroélectrique viendra en concurrence avec un certain nombre d'autres utilisations, surtout agricoles, d'une eau de plus en plus rare. La hausse de la demande en eau pompée et en électricité destinée au refroidissement en été, et la baisse de la demande en hiver, pourraient décaler la demande de pointe vers la saison estivale principalement. Si la baisse du débit d'eau réduisait la production d'hydroélectricité, il pourrait s'ensuivre une augmentation de production des centrales thermiques, donc de la consommation de combustibles fossiles et des émissions de gaz à effet de serre.

Assurances

Les petites compagnies d'assurance et les titulaires de polices pourront ne pas avoir les moyens de couvrir les frais plus élevés liés à la hausse des risques. Les assureurs consentiront peut-être moins à accepter ce risque. Les primes d'assurance-récolte pourront monter, ou bien l'on comptera sur les contribuables pour assumer les coûts supplémentaires.

Le réchauffement planétaire pourra avoir des effets directs sur la santé, comme un accroissement de la mortalité et des maladies due à l'intensité et à la durée des vagues de chaleur, et une baisse de la mortalité liée au froid. Dans les effets indirects, on retrouvera une aggravation des affections respiratoires et allergiques.

Loisirs et tourisme

Les températures plus élevées favoriseront la croissance des algues et des plantes aquatiques, ce qui pourrait tuer des poissons et réduire la pêche d'agrément en bien des endroits. La situation entraînera aussi une baisse de la qualité d'autres activités, comme la baignade et le ski nautique. Avec l'assèchement des étangs qui accompagnera probablement le réchauffement, la production d'oiseaux aquatiques pourrait se trouver réduite.

Demande et approvisionnement en eau

Selon le scénario de MCG retenu, les prévisions du ruissellement dans les Prairies le placent au-dessus ou au-dessous de la normale. Par exemple, certains scénarios prédisent une augmentation des précipitations annuelles moyennes, du nombre d'extrêmes météorologiques, de la fréquence des fortes tempêtes et de l'évaporation, ainsi qu'une diminution du manteau nival et une accélération de sa disparition.

Si les phénomènes extrêmes deviennent plus intenses et plus fréquents, les barrages et autres ouvrages de retenue actuels, conçus en fonction des intensités et fréquences connus par le passé, pourraient être insuffisants.

Avec un temps plus chaud, il faudra disposer de davantage d'eau de boisson de bonne qualité pour le bétail, les animaux sauvages et les populations humaines. Il y aura donc plus de concurrence pour l'utilisation d'une ressource limitée.

Milieu naturel

Les modifications imposées par le changement climatique au cycle hydrologique influeront probablement sur la disponibilité et la qualité d'habitats critiques pour les poissons. Le réchauffement climatique aura des conséquences importantes pour certaines espèces de poissons; en effet, dans de nombreux lacs des latitudes moyennes, les changements survenus jusqu'ici ont déjà amené les températures près du seuil de tolérance thermique de divers organismes. Cependant, la hausse des températures permettra à certaines espèces dulçaquicoles d'étendre leur aire de répartition vers les latitudes plus élevées et pourra leur faire quitter ce qui en est présentement la limite sud.

Ce sont probablement les espèces sauvages liées à des milieux humides semi-permanents ou saisonniers qui seront les plus affectées par le changement climatique dans la région.

ADAPTATION AU CLIMAT

Agriculture

Au cours du dernier siècle, les agriculteurs, surtout dans les régions qui connaissent souvent des déficits extrêmes de l'humidité du sol, se sont adaptés au climat en irriguant leurs cultures. C'était certes une stratégie d'adaptation fort efficace par le passé, mais elle peut être moins intéressante si l'approvisionnement en eau devient plus irrégulier. Une option valide pour certaines régions pourrait être la conversion à des cultures tolérant la sécheresse. En outre, les agriculteurs et les éleveurs ont commencé à se diversifier grâce à des cultures spéciales (p. ex. graine de moutarde, pois secs et lentilles) ou à des espèces indigènes comme le bison et l'élan.

Bien que le secteur de l'agriculture soit en mesure de réagir et de s'adapter aux changements climatiques, les gouvernements joueront un rôle dans les modalités et la vitesse de cette adaptation. Les virages actuels des politiques agricoles commencent à permettre une plus grande souplesse dans la production, non seulement pour ce qui est des techniques, mais aussi quant aux produits.

Écosystèmes forestiers

Différentes stratégies d'adaptation et d'atténuation sont possibles. Par exemple, on peut gérer les peuplements et les paysages de manière à réduire le risque de feux de cimes et d'incendies de grande superficie, gérer le combustible forestier, effectuer des brûlages dirigés, préserver et rehausser la biodiversité, et gérer les paysages forestiers qui sont de plus en plus fragmentés.

L'industrie des produits forestiers peut s'adapter aux changements des écosystèmes en récupérant les arbres mourants, en reboisant avec des espèces mieux adaptées ou en se réinstallant aux endroits où le bois devient plus abondant. Cependant, pour les aspects non forestiers, comme la biodiversité, l'adaptation sera plus difficile.

Parmi les mesures d'adaptation « sans reproches », on peut envisager de mettre en oeuvre une gestion de forêts d'âges variés, de maintenir un couvert forestier, de gérer les forêts en fonction de plusieurs espèces et de modifier les régimes de récolte de manière à protéger les sols et à maintenir la productivité. Ce sont en effet des mesures qui tentent de reproduire les processus naturels.

Énergie

L'industrie et les particuliers pourraient atténuer les impacts du changement climatique par des actions visant à réduire la consommation de combustibles fossiles. Ces mesures, en soi, imposeront au secteur de l'énergie de s'adapter à des changements dans la demande en énergie.

Nombre de compagnies fournisseuses d'énergie ont mis en place des stratégies qui leur permettront d'adapter leurs opérations au changement climatique. Par exemple, il peut s'agir d'une révision des prévisions à long terme de la charge, d'une évaluation de l'adéquité des centrales thermiques par rapport à celle des centrales hydroélectriques dans un contexte de changement climatique, et d'aspects opérationnels comme la recherche sur les effets du givrage sur les conducteurs ou les améliorations des méthodes de calcul de la demande de l'évaporation.

Assurance

Les compagnies d'assurance s'adaptent aux pertes en augmentant les primes et/ou les franchises, en réduisant ou refusant la couverture, ou en rendant la souscription d'un risque conditionnelle à la prise de certaines mesures par l'assuré.

Sur un plan plus concret, une autre possibilité est de réduire l'investissement dans les entreprises qui contribuent aux émissions de gaz à effet de serre. L'industrie fait également des pressions pour que soient adoptés des codes du bâtiment plus stricts quant aux améliorations de l'efficacité énergétique.

Loisirs et tourisme

La clientèle de ce secteur peut s'adapter à la variabilité et au changement climatiques en choisissant d'autres destinations où les conditions soient plus favorables, en réduisant sa participation lorsqu'elles ne le sont pas ou en abandonnant ses activités habituelles. Elle peut aussi se livrer à de nouvelles activités ou accroître sa participation à d'autres.

Demande et approvisionnement en eau

De vastes réservoirs (on compte environ 770 barrages d'importance dans les provinces des Prairies) ont été aménagés sur la presque totalité des grands systèmes hydrographiques de la région. Ces réservoirs piègent le ruissellement printanier, dont ils restituent l'eau pendant les périodes de sécheresse, et réduisent les inondations pendant les périodes de débit de pointe. La plupart sont utilisés à plusieurs fins, dont l'irrigation, la production d'électricité, les loisirs, la protection des collectivités d'aval contre les crues et le transfert d'eau entre bassins versants.

Plus de 110 000 étangs artificiels, desservant des exploitations agricoles ou des collectivités, ont été creusés dans les Prairies pour stocker le ruissellement printanier. Par ailleurs, beaucoup de régions rurales utilisent l'eau souterraine, soit uniquement soit comme appoint à l'eau de surface. Les systèmes régionaux de redistribution de l'eau sont en outre une stratégie d'adaptation de plus en plus courante.

Il existe des politiques et législations officielles de gestion de l'eau visant les systèmes fluviaux traversant les frontières internationales, interprovinciales ou provinciale/territoriale, qui stipulent quelle quantité d'eau peut être utilisée dans chaque domaine de compétence.

AVENUES DE RECHERCHE

Bien que nos connaissances sur le changement et la variabilité climatiques dans les provinces des Prairies aient beaucoup progressé depuis une vingtaine d'années, il reste nombre de domaines sur lesquels faire porter les recherches. On présente ci-dessous quelques sujets généraux de recherche pour chaque secteur. Le lecteur trouvera plus de détails aux diverses annexes.

Agriculture

- Pourquoi les réponses diffèrent-elles, et quelles sont les caractéristiques de l'agriculture qui font que certaines régions sont plus vulnérables ou s'adaptent mieux?
- Quelles conditions non climatiques régissent la possibilité de s'adapter? Quels sont les incitatifs et les limites à l'adaptation?
- Comment l'agriculture peut-elle assurer sa pérennité dans l'éventualité d'un changement climatique?

Écosystèmes forestiers

- De quelle nature sont les interactions actuelles entre le climat et l'écosystème de la forêt boréale? Quels paramètres critiques ne sont pas encore couverts par les activités de surveillance?
- Quel est l'effet net, à court et à long terme, des changements survenus dans la croissance et dans les perturbations?
- Quels changements de l'importance économique des forêts peut-on penser qu'entraîneront les changements climatiques prévus? À quel point l'industrie forestière est-elle sensible à ces changements?

Énergie

- Quelles sont les sensibilités des divers volets du secteur de l'énergie au changement climatique? Comment se comparent-elles à celles d'autres secteurs?
- Quels sont les meilleurs modèles qualitatifs et quantitatifs que l'on puisse utiliser pour estimer les impacts du changement climatique et tester les stratégies d'adaptation?
- Où se situe le point d'équilibre entre l'adaptation et l'atténuation? Quels sont les liens entre les deux?

Assurances

- Comment peut-on améliorer les modèles du climat régional pour aider les compagnies d'assurance à fixer des primes équitables et réalistes face au changement climatique?
- À quels genres de risques peuvent s'attendre les compagnies d'assurance dans la couverture d'éventuels dommages survenant dans les Prairies et liés au climat?

Loisirs et tourisme

- Quels sont les coûts économiques de la création de conditions favorables aux loisirs?
- Quels sont les conflits dus à la concurrence pour des ressources moins abondantes, comme l'eau? Quels instruments, législatifs ou autres, peuvent être élaborés pour régler ces conflits?

Demande et approvisionnement en eau

- Comment peut-on améliorer les modèles du climat régional pour évaluer les impacts du changement climatique sur la demande et l'approvisionnement en eau? Quel est le risque qu'il survienne un plus grand nombre de phénomènes climatiques extrêmes?
- Quelles seront les incidences socio-économiques d'un climat plus chaud sur des secteurs tels que l'utilisation de l'eau par les municipalités, le tourisme et les loisirs, l'agriculture, et la production d'électricité?

Écosystèmes aquatiques

- Quels liens le changement climatique a-t-il avec le cycle hydrologique, et avec le fonctionnement et la structure chimiques et biotiques des écosystèmes aquatiques?
- De quelle manière peut-on intégrer les études de surveillance intensives à court terme avec les données paléo-environnementales et les modèles de prévision quantitative dont on dispose actuellement?

Espèces sauvages et biodiversité

- Quels sont les effets synergiques du rayonnement UV-B, de la chimie de l'eau et des produits chimiques agricoles sur les amphibiens des Prairies canadiennes?
- Quels peuvent être les impacts du changement climatique sur les milieux humides?

PREFACE

INTRODUCTION

The Canada Country Study

Climatic variability and change will impact Canadian people, flora, and fauna, and will have social and economic implications throughout the country. There is an urgent need for a national comprehensive and integrated evaluation of existing knowledge concerning the impacts of climate variability and change on Canada, as well as potential adaptive responses to such changes.

The Canada Country Study (CCS): Climate Impacts and Adaptation responds to this need. In presenting this national perspective, it draws upon studies of a number of regional, sectoral and cross-cutting issues, of which this volume is one.

The study was initiated by Environment Canada (EC) and is being lead by the Environmental Adaptation Research Group, a component of EC's Atmospheric Environment Service located in Downsview, Ontario. Among the participants are representatives of various levels of government, the university community, the private sector and non-governmental organizations.

In providing Canadians with a balanced, realistic picture of what climate change and variability means for Canada as a whole, the CCS effort builds upon a number of sectoral and regional impact studies that have been completed during the past decade. These studies tend to emphasize one of three approaches: i) modelling - generally quantitative analysis of impacts associated with a range of climate change scenarios; ii) monitoring - real time observations of environmental response to recent and ongoing climate variability; and, iii) paleoenvironmental analysis - utilizing past environmental changes and proxy climate data to provide analogues for impacts of future climate change.

The CCS will provide information to Canadian policy makers in the public and private sectors, socio-economic decision makers, the scientific community both domestically and internationally, non-governmental organizations, and the general public.

Work on the CCS is divided into two phases. Phase I began in the summer of 1996 and will conclude in the fall of 1997. Phase I, the subject of this report, determines '*where we are now*' by synthesizing existing impacts and adaptation research for selected climate-sensitive sectors in the three Prairie Provinces, the identification of knowledge gaps, and the development of recommendations for future research. It also builds *regional involvement* of federal, provincial, academic and NGO people.

Phase II, which is expected to begin in late 1997 and extend over approximately a five-year period, will address the knowledge gaps and recommendations for future research.

In Phase I, a number of summary reports will be published - a national policy makers summary, a national plain language summary, and six regional plain language summaries. In addition, the basis of these summaries - 25 component studies and papers - are being published in eight volumes as follows:

- Vol. I - British Columbia and Yukon
- Vol. II - Arctic
- Vol. III - Prairies
- Vol. IV - Ontario
- Vol. V - Québec
- Vol. VI - Atlantic
- Vol. VII - Sectoral (comprising 12 national papers on agriculture, built environment, energy, fisheries, forestry, human health, insurance, recreation and tourism, transportation, unmanaged ecosystems, water resources and wetlands)
- Vol. VIII - Cross-Cutting (comprising seven national papers on changing landscapes, domestic trade and commerce, extra-territorial influences, extreme events, integrated air issues, sustainability, and the two economies).

Report structure

Eight key climate-sensitive areas or sectors in the Prairie Provinces were selected for analysis. These are: agriculture, forestry, energy, insurance, recreation/tourism, water supply and demand, aquatic ecosystems, and wildlife and biodiversity. These sector assessments were prepared by experts and were subjected to detailed external review. A ninth assessment, summarizing our knowledge of proxy records of postglacial climate in the Prairie Provinces, was also prepared. The assessments, attached to this volume as appendices, form the basis of this report.

The eight sector assessments were based primarily on the author's knowledge and review of the applicable literature. The authors were guided in this task by the following questions (note that the questions are designed to focus the author and to stimulate thought, and may be less important for some sectors while other questions may be more important):

1. *Why might climate change be a problem for this sector?*
2. *What do we know about the connection between current climate variability, including current climate extremes, and this sector (if anything)? How sensitive might this sector be to a warmer and a wetter or drier climate?*
3. *What may occur in this sector of the economy or the environment if a global warming occurs over the next 50 to 80 years? (This will be based on a review of the literature, the author's knowledge and hypothetical "What-if" scenarios).*
4. *So what? Will these changes affect people in any way? (For example, will the climate change impacts outlined in question 3 have any impact on human activities such as urban development, tourism, agriculture, trade, social problems, conflicts such as water vs. free trade, competition for hydroelectric power, land claims etc.).*
5. *Will other effects, for example population growth or forest over-harvesting, overwhelm any climate change impacts on people? Or will climate change exacerbate these other effects?*
6. *What should be done? While there is a need for more plausible climate change predictions in the Prairies, is more research needed on climate change impacts, and if so, where should we concentrate? Should we focus on reducing greenhouse gas emissions? Should we develop and begin the implementation of some sort of adaptation measures?*

The report is organized into six chapters. The first two chapters provide the regional context of geography, population, economics and climate. The other four chapters summarize our knowledge of regional climate sensitivities, possible climate change impacts, climate adaptations, and opportunities for further research. The Executive Summary identifies the key points made in this report.

Acknowledgements

The generous support of the following sector authors is gratefully acknowledged: Allen Tyrchniewicz, Quentin Chiotti, Elaine Wheaton, Malcolm Wilson, Marion Meyer, Brian Johnson, Cheri Gratto-Trevor, Kevin Cash and David Sauchyn. Ron Blackwell, Ted O'Brien, Don Lemmen, Brian Mills, Garry Schaefer, Elaine Wheaton and Malcolm Wilson also provided timely and constructive comments on this volume. Their suggestions have improved significantly the final product.

Special appreciation is extended to staff of the Saskatchewan Research Council (Saskatoon), Saskatchewan Energy and Mines (Regina), and the International Institute for Sustainable Development (Winnipeg) for their support.

THE CLIMATE BACKGROUND

Climate change and variability

Climate may be thought of as a description of the regularities and extremes in weather for a particular location. It is also, however, naturally variable; from our own experience, we know that one summer is often warmer than another, or one winter is colder or snowier than another. Such variability is a normal feature of a stable climate, and is related to changes in ocean currents or sea-surface temperatures, volcanic eruptions, alterations in the sun's output of energy, or other complex features of the climate system some of which are not yet fully understood. It is not safe to assume that the variability of the present climate system is adequately represented by the comparatively short instrumental meteorological record, and hence it is important to integrate this record with proxy climate data derived from ice cores, tree rings, lake sediments and other sources to assess climate dynamics.

Natural large-scale climate shifts (or climate changes, such as those that resulted in past ice ages or warm interglacial periods) are driven by long-term alterations in the position of the Earth with respect to the sun. Such alterations can be reflected in changes in the composition of the Earth's atmosphere, an important characteristic of which is the occurrence of certain greenhouse gases (such as carbon dioxide and methane). These gases keep the Earth's surface and atmosphere from cooling too rapidly and help to maintain surface temperatures within the range needed to support life.

Greenhouse gas concentrations have been observed to be lowest during periods of cold climate (ice ages) and highest during warm periods. This connection is of concern because human activities since the beginning of the industrial revolution over 200 years ago (mainly involving the burning of fossil fuels) have greatly increased the concentration of such gases in the atmosphere. Scientists expect to see a doubling of the atmospheric composition of carbon dioxide, for example, within the next century. The increase so far is already considered to have had a discernible effect on the Earth's climate, an effect which is expected to continue.

Models and scenarios

In order to understand how the world's climate may respond, elaborate supercomputer models of the climate system are used. Known as general circulation models or GCMs, these models are used to simulate the type of climate that might exist if global concentrations of carbon dioxide were twice their pre-industrial levels. Although the models disagree about many of the details of a doubled carbon-dioxide climate, the results of the simulations all agree that the Earth would be warmer, on average (with more warming occurring towards the poles), and would experience overall increases in both evaporation and precipitation. These simulations of climate are referred to as "GCM-driven scenarios" - distinct from actual forecasts for the future - since they depict a possible future based on certain assumptions about atmospheric composition. The most recent report of the Inter-governmental Panel on Climate Change (IPCC - *qui vive*), issued in 1995, projects an increase in global surface temperature of 1 to 3.5^{o}C over the next 100 years. This may be compared with the observed increase of 0.3 to 0.6^{o}C over the past 100 years.

For its first Phase, the CCS does not follow a single climate scenario. It reflects the range of scenarios that have been used as a basis for the various papers and reports appearing in the scientific literature. In general, the main model scenarios used come from one of five GCMs which have been developed in Canada, the United States, or the United Kingdom.[*]

While there is an increasing level of comfort with the validity of GCM results at the global scale, such comfort decreases when we look at the regional scale. For Canada there are broad areas of agreement in model results including warming over much of the western and northern areas, but there is also some disagreement between models as to the location and magnitude of areas of surface temperature or precipitation change, particularly in eastern Canada. This disagreement is reflected in the words of uncertainty that appear at times in this volume of the Canada Country Study.

THE INTERNATIONAL CONTEXT

International concern about the future of our climate has been building steadily over the past 20 years. One of the first important international conferences to look at the issue was held in Canada in 1988 - The Changing Atmosphere: Implications for Global Security. Also that year, the IPCC was established by the World Meteorological Organization and the United Nations Environment Programme with a mandate to assess the science of climate change, its environmental and socio-economic impacts, and possible response strategies. The IPCC subsequently published formal assessments in 1990 and 1995, with a third to follow in 2000 or 2001.

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- CCC92 - Canadian Centre for Climate Modelling and Analysis 2nd Generation model
- GFDL91 - Geophysical Fluid Dynamics Laboratory model (US)
- GISS85 - Goddard Institute for Space Studies model (US)
- NCAR93 - National Center for Atmospheric Research model (US)
- UKMO95 - UK Meteorological Office model

In 1992, the United Nations Conference on Environment and Development was held in Rio de Janeiro and resulted in consensus on a Framework Convention on Climate Change (FCCC). This Convention's objective is "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". It has now come into force and involves commitments to actions including emissions reductions, assistance to developing nations, reporting on emissions inventories, scientific and socio-economic research to reduce uncertainties, as well as education and training. Canada's domestic response to the FCCC has been its National Action Program on Climate Change.

To date, as the objective of the FCCC would suggest, much of the international emphasis on response strategies for dealing with the impacts of climate change has focussed on reducing emissions of greenhouse gases. A very important complement to such reductions is the need to understand the impacts of and to adapt to changing climate. The Canada Country Study is one of Canada's responses to recognizing the importance of climate impacts and adaptation.

CLIMATE IMPACTS AND ADAPTATION

The major concern arising from the climate change issue is the impact it may have on our environment, our economy, and therefore, on the way we live both now and in the future.

In Canada, we are accustomed to dealing with variations in climate both geographically and seasonally across the country. These variations have many impacts that can reverberate through natural and man-made systems, including water resources, vegetation and wildlife, agricultural practice, forestry and fisheries, energy supply and demand, buildings and roads, recreation and tourism, the insurance industry, and human health.

At present, there are many good examples of our ability to adapt to the range of current climate conditions which we face collectively in our economy and as individuals in our everyday life. If we depend upon wildlife species for sustenance, we follow them when migratory routes change; we plant different types of crops in different locations at different times of the year; we construct roads and buildings using designs that are compatible with ground conditions or with differing snow and wind loads; we build ships and other marine platforms capable of withstanding expected wave heights and sea-ice conditions; we locate recreational facilities and events where they can benefit from appropriate climate conditions, such as sufficient snow for skiing or enough wind for sailing.

Although considerable uncertainties exist about the nature of future climatic changes and particularly their associated regional impacts, this does not preclude a proactive approach to the development of adaptive strategies. GCMs now are able to provide a reasonable range for climatic parameters under enhanced CO_2 conditions, and analogues for all but the most extreme of these can be found in the last 10 000 years of the earth's history. These analogues allow identification of critical vulnerabilities in environmental systems in the absence of significant human impact. Assessment of future impacts must integrate these natural vulnerabilities with the increasing stresses imposed by human activities.

When thinking about adaptation as a way to respond to current climate and we then consider an on-going climate change and its impacts, we look for answers to the following questions so that our future planning can be done most effectively:

- What are the impacts of a changing climate and how will they affect me and my family through our lives?
- Are decisions being made today which will increase our vulnerability in the future because they are not taking such impacts into account?
- Will the approaches we use to adapt to the current climate still be workable in the future, or will new approaches be necessary to adapt to changes beyond our historical experience?
- Will the rate of changing climate allow enough time to adapt?
- Should society become more adaptable or flexible to changes in climate than it is now, and if so, how?

The Canada Country Study is aimed at helping to answer some of these questions.

PREFACE

INTRODUCTION

L'Étude pancanadienne

Le changement et la variabilité climatiques auront des répercussions pour la population du Canada, sa faune et sa flore, et leurs conséquences sociales et économiques se feront sentir dans tout le pays. Il est donc urgent de dresser un bilan national exhaustif et intégré des connaissances actuelles quant aux impacts du changement et de la variabilité climatiques sur le Canada, ainsi que d'examiner quelles mesures d'adaptation peuvent être prises face à ces changements.

C'est ce besoin que doit combler l'Étude pancanadienne (EP) sur l'adaptation à la variabilité et au changement climatiques. Pour présenter cette perspective nationale, on a utilisé des études sur un certain nombre de questions régionales, sectorielles et intersectorielles, dont fait partie ce volume.

Cette étude a été entreprise par Environnement Canada (EC) et est dirigée par le Groupe de recherche en adaptation environnementale, composante du Service de l'environnement atmosphérique d'Environnement Canada, dont les bureaux sont à Downsview (Ont.). Parmi les participants à cette étude figurent des représentants de différents paliers de gouvernement, du milieu universitaire, du secteur privé et d'organisations non gouvernementales.

Afin de fournir aux Canadiens une image juste et réaliste de ce qu'impliquent le changement et la variabilité climatiques pour l'ensemble du Canada, l'EP a fait fond sur un certain nombre d'études d'impact régionales et sectorielles qui ont été réalisées dans la dernière décennie. Ces études adoptent en général une des trois approches suivantes : i) la modélisation, qui est une analyse généralement quantitative des impacts liés à divers scénarios de changement climatique, ii) la surveillance, qui consiste à exécuter des observations en temps réel de la réponse de l'environnement à la variabilité climatique de l'époque récente et actuelle, et iii) l'analyse paléo-environnementale, qui utilise les changements environnementaux passés et des données climatologique substitutives pour fournir des analogues des impacts d'un changement climatique futur.

L'Étude pancanadienne fournira de l'information aux décideurs canadiens des secteurs public et privé, aux décideurs du domaine socio-économique, à la communauté scientifique nationale comme étrangère, aux organisations non gouvernementales, ainsi qu'à l'ensemble des Canadiens.

Les travaux de l'EP se divisent en deux étapes. L'étape I, qui a été entreprise à l'été 1996 et prendra fin à l'automne 1997, est l'objet du présent rapport. Il s'agissait de dresser un « état des lieux » en faisant une synthèse des recherches actuelles sur les impacts et l'adaptation pour certains secteurs tributaires du climat des trois provinces des Prairies, de repérer les lacunes dans les connaissances et d'élaborer des recommandations pour les recherches à venir. L'étape I repose aussi sur la participation régionale de représentants du gouvernement fédéral, des gouvernements provinciaux, du milieu universitaire et d'organisations non gouvernementales.

L'étape II, qui devrait commencer à la fin de 1997 et se prolonger sur environ cinq ans, se penchera sur les lacunes des connaissances et sur les recommandations pour les recherches futures.

L'étape I débouchera sur la publication d'un certain nombre de rapports de synthèse, soit un résumé national à l'intention des décideurs, ainsi qu'un résumé national et six résumés régionaux de vulgarisation. De plus, les rapports généraux sur lesquels sont fondés ces résumés, soit un regroupement de 25 études et documents, seront publiés en huit volumes, comme suit :

- Vol. I - Colombie-Britannique et Yukon
- Vol. II - Arctique
- Vol. III - Prairies

- Vol. IV - Ontario
- Vol. V - Québec
- Vol. VI - Atlantique
- Vol. VII - Questions sectorielles (12 documents nationaux sur l'agriculture, le milieu bâti, l'énergie, les pêches, la foresterie, la santé humaine, les assurances, les loisirs et le tourisme, les transports, les écosystèmes naturels, les ressources en eau et les terres humides).
- Vol. VIII - Questions intersectorielles (8 documents nationaux sur la transformation des paysages, les frais, le commerce intérieur, les influences extra-territoriales, les phénomènes extrêmes, les questions atmosphériques intégrées, la durabilité et les deux économies).

Structure du rapport

On a choisi d'analyser huit secteurs clés des Prairies qui sont tributaires du climat, soit : l'agriculture, la foresterie, l'énergie, les assurances, les loisirs et le tourisme, l'approvisionnement et la demande en eau, les écosystèmes aquatiques, ainsi que les espèces sauvages et la biodiversité. Ces évaluations sectorielles ont été effectuées par des experts et soumises à un examen détaillé à l'externe. Une neuvième évaluation, résumant notre connaissance des enregistrements substitutifs du climat post-glaciaire dans les provinces des Prairies, a également été faite. Ce sont ces neufs documents, que l'on trouvera en annexe, qui constituent la base du présent rapport.

Les huit évaluations sectorielles reposent essentiellement sur les connaissances de l'auteur et sur l'examen qu'il a fait de la littérature pertinente. Les travaux des auteurs ont été guidés par les questions suivantes (à noter que ces questions visent à orienter et stimuler la réflexion de l'auteur, et peuvent présenter plus ou moins d'importance selon les secteurs examinés) :

1. *Pourquoi le changement climatique pourrait-il poser un problème dans ce secteur?*

2. *Que savons-nous de la relation, s'il y en a une, entre la variabilité climatique actuelle, y compris les présents extrêmes, et le secteur d'intérêt? Quelle est la sensibilité du secteur à un changement qui rendrait le climat plus chaud et plus humide ou plus sec?*

3. *Que pourrait-il se produire dans ce secteur de l'économie ou de l'environnement si un réchauffement planétaire prenait place au cours de 50 ou 80 prochaines années? (La réponse sera basée sur un examen de la littérature, les connaissances de l'auteur et des scénarios de changement.)*

4. *Que se passera-t-il? Les changements auront-ils une quelconque incidence sur la population? (Par exemple, les impacts du changement climatique définis dans la réponse à la question 3 auront-ils des répercussions sur des activités humaines telles que le développement urbain, le tourisme, l'agriculture, le commerce? Influeront-ils sur les problèmes sociaux, les situations de conflit telles que l'accès à l'eau vs le libre-échange, la concurrence pour la production d'hydroélectricité, les revendications territoriales, etc.?)*

5. *D'autres effets, comme la croissance démographique ou la surexploitation des forêts, prendront-ils plus d'importance que ceux du changement climatique sur la population? Le changement climatique va-t-il exacerber ces effets?*

6. *Que faudrait-il faire? On sait qu'il faut pouvoir disposer de prédictions plus plausibles du changement climatique dans les Prairies, mais faut-il poursuivre des recherches sur ses impacts? Si oui, sur quoi devraient-elles être ciblées? Sur les émissions de gaz à effet de serre? Devrions-nous élaborer des mesures d'adaptation et commencer à les mettre en place?*

Le rapport est organisé en six chapitres. Les deux premiers brossent un tableau de la région : géographie, population, économie et climat. Les quatre suivants résument nos connaissances sur sa sensibilité au climat, sur les impacts possibles du changement climatique, sur l'adaptation à ces changements et sur les avenues de recherche futures. Le résumé met en relief les points clés présentés dans le rapport.

Remerciements

Nous tenons à remercier chaleureusement les auteurs suivants pour leur généreux appui : Allen Tyrchniewicz, Quentin Chiotti, Elaine Wheaton, Malcolm Wilson, Marion Meyer, Brian Johnson, Cheri Gratto-Trevor, Kevin Cash et David

Sauchyn. Ted O'Brien, Don Lemmen, Brian Mills, Garry Schaefer, Elaine Wheaton et Malcolm Wilson ont également fourni des commentaires pertinents et constructifs sur le volume. Leurs recommandations ont considérablement contribué à la qualité du produit final.

Nous remercions aussi particulièrement pour leur appui les personnels du Saskatchewan Research Council (Saskatoon), du ministère de l'Énergie et des Mines de la Saskatchewan (Regina) et de l'Institut international du développement durable (Winnipeg).

HISTORIQUE DU CLIMAT

Changement et variabilité climatiques

On peut considérer le climat comme une description des constantes et des extrêmes des conditions météorologiques d'un endroit donné. Par contre, le climat est naturellement variable. Ainsi, nous en avons l'expérience, il arrive souvent qu'un été soit plus chaud qu'un autre, ou un hiver plus froid ou plus neigeux qu'un autre. Cette variabilité est une caractéristique normale d'un climat stable, et tient aux fluctuations des courants océaniques ou des températures des eaux de surface de la mer, aux éruptions volcaniques, aux modifications de l'émission d'énergie par le Soleil, ou à d'autres caractéristiques complexes du système climatique dont certaines ne sont pas encore parfaitement comprises. On ne saurait raisonnablement penser que la variabilité du système climatique actuel est bien représentée par l'enregistrement météorologique instrumental relativement court dont nous disposons; il est donc important, pour évaluer la dynamique du climat, d'intégrer à cet enregistrement des données climatologiques substitutives tirées des carottes de glace, des cernes de croissance des arbres, des sédiments lacustres et d'autres sources.

Les variations naturelles à grande échelle du climat (ou les changements climatiques, comme ceux qui se sont traduits par les glaciations et les périodes interglaciaires chaudes du passé) sont le résultat de modifications à long terme de la position de la Terre par rapport au Soleil. Ces modifications peuvent induire des changements dans la composition de l'atmosphère terrestre, dont l'une des caractéristiques importantes est la présence de certains gaz à effet de serre (comme le dioxyde de carbone et le méthane). Ces gaz protègent la surface et l'atmosphère de la Terre contre un refroidissement trop rapide et aident à maintenir les températures de surface dans la plage nécessaire au maintien de la vie.

On a observé que les concentrations de gaz à effet de serre étaient plus basses durant les périodes de climat froid (périodes glaciaires) et plus élevées durant les périodes chaudes. Cette relation est préoccupante car, depuis le début de la révolution industrielle, il y a plus de 200 ans, les activités humaines (surtout la combustion de combustibles fossiles) ont provoqué une forte augmentation de la concentration de ces gaz dans l'atmosphère. Selon les scientifiques, on pourrait assister, dans le prochain siècle, à un doublement de la concentration de dioxyde de carbone dans l'atmosphère. On considère que l'augmentation survenue à ce jour a déjà eu un effet perceptible sur le climat de la Terre, effet qui devrait se poursuivre.

Modèles et scénarios

Pour comprendre comment pourrait réagir le climat mondial, on utilise des modèles complexes du système climatique tournant sur superordinateur. Connus sous l'appellation de « Modèles de circulation générale » ou MCG, ces modèles servent à simuler le type de climat qui pourrait exister si les concentrations planétaires de dioxyde de carbone doublaient par rapport aux niveaux de l'ère préindustrielle. Bien que les modèles divergent sur nombre des détails d'un climat à double CO2, l'ensemble des simulations confirment que le climat de la Terre serait généralement plus chaud (avec un réchauffement plus marqué près de pôles), et qu'il y aurait une augmentation globale de l'évaporation et des précipitations. Ces simulations du climat, appelées « scénarios issus des MCG », ne sont pas des prévisions comme telles, mais décrivent un futur éventuel fondé sur certaines hypothèses quant à la composition de l'atmosphère. Le plus récent rapport du Groupe d'experts intergouvernemental sur l'évolution du climat (GIEC - cf. infra), publié en 1995, prévoit un réchauffement de la surface du globe variant entre 1 °C et 3,5 °C au cours du prochain siècle; il convient de comparer ces valeurs avec le réchauffement de 0,3 °C à 0,6 °C observé au cours du dernier siècle.

Pour sa première étape, l'Étude pancanadienne sur le climat ne suit pas un scénario climatique unique. Elle prend plutôt en compte toute la gamme de scénarios sur lesquels se sont fondés les spécialistes pour préparer les différents documents et rapports parus dans la littérature scientifique. D'une façon générale, les principaux scénarios utilisés proviennent de l'un des cinq MCG mis au point au Canada, aux États-Unis ou en Angleterre.[*]

Bien que l'on ait de plus en plus confiance dans la validité des résultats fournis pas les MCG à l'échelle planétaire, cette confiance s'érode lorsque l'on descend à l'échelle régionale. Pour le Canada, on constate de vastes secteurs de concordance entre les résultats des différents modèles, notamment le réchauffement du climat dans une grande partie de l'ouest et du nord; mais il y a également certaines divergences en ce qui concerne la localisation et l'ampleur des transformations qui toucheront les températures de surface et les régimes de précipitations, particulièrement dans l'est du Canada. L'incertitude exprimée à certains endroits dans le présent volume de l'Étude pancanadienne traduit ce désaccord.

LE CONTEXTE INTERNATIONAL

Au cours des 20 dernières années, l'avenir du climat mondial est devenu une préoccupation de plus en plus constante à l'échelle internationale. L'une des plus importantes conférences internationales sur cette question s'est déroulée au Canada en 1988 et s'intitulait « L'Atmosphère en évolution : implications pour la sécurité du globe ». Cette même année, le GIEC a été créé conjointement par l'Organisation météorologique mondiale et le Programme des Nations Unies pour l'environnement, avec le mandat d'évaluer les données scientifiques disponibles sur l'évolution du climat, les incidences écologiques et socio-économiques de cette dernière, et de formuler des stratégies de parade. Le GIEC a ensuite publié deux rapports d'évaluation en 1990 et 1995, et un troisième devrait suivre en l'an 2000 ou 2001.

En 1992 se tenait à Rio de Janeiro la Conférence des Nations Unies sur l'environnement et le développement, dont les travaux ont permis d'en arriver à un consensus quant à une Convention-cadre sur les changements climatiques (CCCC). L'objectif ultime de la Convention est de « stabiliser les concentrations de gaz à effet de serre dans l'atmosphère à un niveau empêchant toute perturbation anthropique dangereuse du système climatique ». La Convention est maintenant en vigueur et comporte des engagements relatifs à certaines mesures comme la réduction des émissions, l'aide aux pays en développement, la préparation de rapports sur les inventaires d'émissions, l'exécution de recherches scientifiques et socio-économiques en vue de lever les incertitudes, ainsi que des activités d'information et de formation. En réponse à la CCCC, le Canada a mis au point son propre Plan national d'action sur le changement climatique.

À ce jour, conformément à l'objectif de la CCCC, la majorité des efforts déployés à l'échelle internationale pour élaborer les stratégies de parade face aux impacts des changements climatiques ont surtout porté sur la réduction des émissions de gaz à effet de serre. Étant donné que nous devrons composer longtemps avec les changements climatiques, il est important de comprendre leurs incidences et de nous y adapter, en plus d'effectuer ces réductions. L'Étude pancanadienne est l'une des réactions du Canada devant l'importance de ces incidences et de l'adaptation nécessaire.

CLIMAT : IMPACTS ET ADAPTATION

Les impacts qu'il peut avoir sur notre environnement, sur notre économie et, par conséquent, sur notre mode de vie actuel et futur sont la principale préoccupation liée au changement climatique.

Au Canada, nous sommes habitués à composer avec les variations de climat qui se manifestent dans tout le pays, aussi bien d'une région à l'autre que d'une saison à l'autre. Ces variations ont de nombreux impacts, qui peuvent se répercuter sur les systèmes naturels et anthropiques, notamment les ressources en eau, la végétation et la faune, les pratiques agricoles, la foresterie et les pêches,

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- CCC92 - Centre canadien de modélisation et d'analyse climatiques, modèle de 2^{e} génération.
- GFDL 91 - Modèle du Geophysical Fluid Dynamics Laboratory (États-Unis)
- GISS85 - Modèle du Goddard Institute for Space Studies (États-Unis)
- NCAR93 - Modèle du National Center for Atmospheric Research (États-Unis)
- UKMO9 - Modèle du Bureau météorologique du Royaume-Uni

la production et la consommation d'énergie, les bâtiments et les routes, les loisirs et le tourisme, l'industrie de l'assurance et la santé humaine.

Il y a déjà nombre de bons exemples de notre capacité d'adaptation à la diversité des conditions climatiques auxquelles nous devons faire face, aussi bien collectivement dans notre économie qu'individuellement dans notre vie quotidienne. Si notre subsistance dépend de la présence d'espèces sauvages, nous les suivons lorsqu'elles modifient leurs voies de migration; nous plantons des types de cultures différents selon les endroits et le moment de l'année; nous construisons les routes et les bâtiments différemment selon que nous sommes ou non sur du pergélisol, ou en fonction de différentes charges de neige et de vent; nous construisons des navires et des plates-formes marines qui peuvent résister aux hauteurs de vagues et aux conditions des glaces de mer prévues; nous aménageons les installations de loisirs et organisons les événements de manière qu'ils bénéficient de conditions climatiques favorables, comme assez de neige pour le ski ou assez de vent pour la voile.

Si l'on considère l'adaptation comme une façon de réagir face au climat actuel, et que l'on examine un changement climatique en cours et ses impacts, on doit répondre aux questions suivantes pour planifier l'avenir le plus efficacement possible :

- Quels sont les impacts du changement climatique, et de quelle façon viendront-ils se répercuter sur ma vie et celle de ma famille?
- Prend-on aujourd'hui des décisions qui viendront accroître notre vulnérabilité future parce qu'elles ne tiennent pas suffisamment compte de ces impacts?
- Les approches que nous utilisons pour nous adapter aux conditions climatiques actuelles seront-elles encore viables dans l'avenir, ou faudra-t-il en envisager de nouvelles pour nous adapter à des changements dépassant tout ce que nous avons connu?
- La vitesse à laquelle se produiront les changements climatiques nous laissera-t-elle le temps de nous adapter?
- Le société devra-t-elle devenir plus adaptable et plus souple qu'elle ne l'est maintenant face aux changements climatiques et, si oui, comment?

L'Étude pancanadienne a pour objectif de nous aider à répondre à certaines de ces questions.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

REGIONAL CONTEXT

INTRODUCTION

This chapter briefly describes the physical setting of the Prairie Provinces, including the topography, soils, characteristic vegetation, river systems and ecozones. The socioeconomic context is also described. This includes trends in population and trends in economic activity, as demonstrated by Gross Domestic Product, primary and secondary industries, and natural resource utilization.

The importance of climate, landscape and natural resources is apparent in the economic dominance of agriculture in this region. Wheat continues to be the dominant crop but oilseed production, such as canola, tends to increase when wheat prices fall. Agricultural diversification is becoming more common. Mining, particularly the production of fuels, is the second most important primary industry in the Prairie Provinces but the area also sustains a healthy manufacturing industry, focused mainly on primary processing of food products, wood, metals, chemicals and petrochemicals. Economic growth in the tertiary sector has been significant, but has been largely confined to private sector industries such as transportation and communication. Growth in the public service sector has been negative or at best weak. Water use has increased in most sectors faster than population growth, particularly for irrigation and the generation of electrical energy.

THE PHYSICAL ENVIRONMENT

The western provinces of Alberta, Saskatchewan and Manitoba are frequently referred to as the Prairie Provinces. They cover a total area of about 196 million hectares. Of this, about 20 million hectares, or 10 percent, is surface water (Table 1).

All three provinces have the 49th parallel as their southern border and the 60th parallel as their northern border. The area lies immediately east of the Rocky Mountain Cordillera of North America. This mountain barrier has a pronounced effect on climatic conditions and in the establishment of ecozone boundaries across the Prairies. The predominant feature of the prairie landscape is one of plains or rolling terrain occasionally interrupted by low to moderate hills and broad, occasionally deep, melt water channels with small to moderate, frequently ephemeral, rivers.

Land elevations are the highest in southwest Alberta (exceeding 1500 m) and decrease to sea level along the Manitoba coastline of Hudson Bay. Prominent hills can be found in all three provinces. These include the Cypress Hills, Swan Hills, and Caribou Mountains (Alberta), the Cypress, Pasquia and Mostoos Hills (Saskatchewan) and the Riding and Duck Mountains (Manitoba).

Table 1. Surface areas of Alberta, Saskatchewan and Manitoba (million hectares)

Province	Land Area	Water Area	Total Area
Alberta	64.4	1.7	66.1
Saskatchewan	57.0	8.2	65.2
Manitoba	54.8	10.2	65.0
Total	176.2	20.1	196.3

The major river systems in Alberta include the North and South Saskatchewan, and the Slave. The Slave comprises 90 percent of the province's water outflow. The major tributaries of the Slave are the Athabasca and Peace rivers. The major river system in Saskatchewan is the Saskatchewan River. The northern part of the province is interlaced with a vast array of rivers flowing through the numerous Precambrian lakes. The major river systems in Manitoba include the Nelson, Churchill and Seal. There are significant hydro-electric generating stations in northern Manitoba.

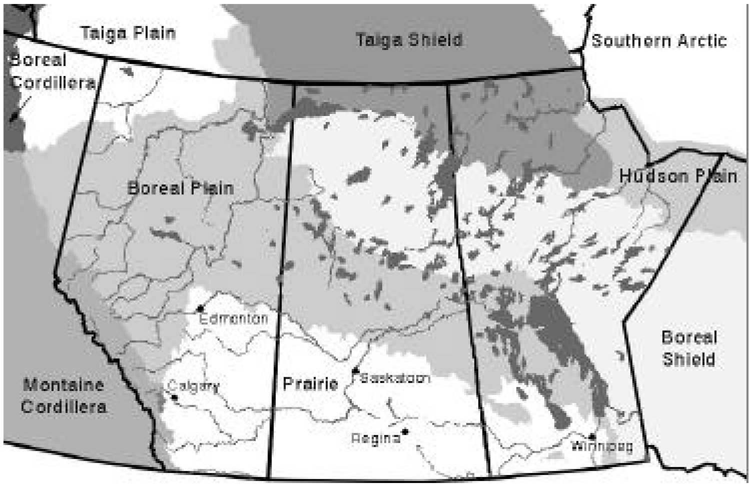
Southern Alberta and Saskatchewan contains several large closed or internal drainage basins which have no surface outflow even under extremely wet conditions. This area of approximately 80 000 km^2 represents the only significant area of internal drainage in all of Canada. Because there is no outflow, surface runoff is balanced by evaporation, depending upon interchange with groundwater systems. In wet years the lakes in the basins enlarge and in dry years they shrink or disappear. Evaporation and groundwater discharge usually result in the lakes being very saline. These basins are good indicators of climate variability and change.

Eight of Canada's fifteen terrestrial ecozones are present in the Prairie Provinces (Figure 1 and Table 2). The two largest are the prairie and boreal plain zones. Approximately one-quarter of the area (45 million hectares) lies in the prairie ecozone and 35 percent (68 million hectares) lies in the boreal plain ecozone.

The soils of the prairie region are primarily of glacial moraine and lacustrine origin. Due to the terrestrial disturbances associated with agriculture, there have been considerable stresses placed on many indigenous bird and mammal species. The soils of the boreal plain are generally sandy glacial deposits overlying the Precambrian Shield. This region supports a vast forest of mixed variety in the south and primarily coniferous species in the north. Since large tracts of virgin forest still remain, the impacts of forestry have not yet had a profound effect on most mammals and birds of this ecozone.

The boreal shield ecozone is dominated by numerous lakes set in gently rolling uplands and lowlands with frequent rock outcroppings. Lack of soil and poor soil fertility (generally a coarse sand aggregate), along with the harsh climate, restrict the vegetation of the boreal shield to generally a less valuable boreal forest flora than in the boreal plain ecozone.

Figure 1. Terrestrial ecozones of the Prairie Provinces



The Southern Arctic ecozone occupies just a sliver of Manitoba along the Hudson Bay coastline north of Churchill. Here the extremely harsh climatic conditions restrict vegetation to tundra and wetland species. The Taiga Shield encompasses a large

area in northern Manitoba and a smaller area in northeastern Saskatchewan. Here the harsh climatic conditions, poor soils and discontinuous permafrost result in open woodlands of stunted coniferous trees, lichen, and wetland and tundra species.

Table 2. Ecozone biophysical characteristics

The northeastern portion of Manitoba is in the Hudson Plains ecosystem. This generally flat plain area has relatively fertile soils but the climatic conditions restrict vegetative growth. Open woodlands of small coniferous trees and dense sedge-moss-lichen covered wetlands dominate the landscape.

Ecozone	Characteristics	Climate	Vegetation	Soils, Surface Materials
Prairie	plains, some foothills	cold winters, warm to hot summers, moderate to minimal precipitation	short and mixed grasslands, aspen parkland	organically rich, relatively fertile grasslands soil, moraine and lake bottom materials
Boreal Plains	plains, some foothills	cold winters, warm to hot summers, moderate precipitation	conifer and broadleaf forest stands, peatlands	temperate region soils with clay-rich sub-layers, moraine and lake bottom materials
Boreal Shield	plains, uplands, interior hills, many lakes and streams	long cold winters, warm summers, moderate precipitation	conifer and broadleaf forests	acid and well weathered soils, lake bottom soils, moraine, rock
Taiga Plain	plains, uplands, interior hills	long cold winters, short warm summers, moderate to minimal precipitation	conifer and broadleaf forests	organic soils, some frozen soils (cryosols), rock
Taiga Shield	plains, some uplands, some interior hills, many lakes and streams	long cold winters, short warm summers, moderate precipitation	open woodlands, some arctic tundra, extensive lichens and heaths	soils with minimum weathering (brunsols), frozen soils, organic soils, moraine, rock
Hudson Plain	generally wide, level plains	long cold winters, short mild summers, minimal precipitation	wetlands, arctic tundra, some conifer stands	organic soils, sea bottom and beach materials, frozen soils
Southern Arctic	rolling lowland plains, wetlands	long cold winters, short cool summers, minimal precipitation	arctic tundra, lichens, heaths, sedge-moss	frozen soils, moraine, rock, marine bottom sediments
Montane Cordillera	mountains, hills, plateaus, valleys	cool winters, warm to hot summers, minimal to moderate precipitation	coniferous forests (frequently open), grasslands,	moraine, rock, soils with minimum weathering

POPULATION TRENDS

Alberta

As of 1995, a total of about 2.75 million people resided in Alberta (Table 3). From 1971 to 1995, the population increased by 64.3 percent which is almost twice the average rate for Canada during the same period. More than 65 percent of the people live in one of the 15 cities in Alberta. The two largest cities, Calgary and Edmonton, account for about 28 percent and 24 percent of the population, respectively (Alberta Environmental Protection, 1995).

The area around Calgary experienced the highest rate of growth of all rural areas in the Prairies during the 1970s and 1980s. This amounted to about a 29 percent increase. This was followed closely by the area around Edmonton. Rapid urban growth rates were experienced in several communities in southeastern Alberta. This may be the result of the more diversified economic base there, including irrigation, agriculture and intensive livestock, a large oil and natural gas industry, and existing large centres.

Saskatchewan

Saskatchewan's population was slightly more than 1 million people in 1995 and has been relatively stable over the past 25 years (Table 3). About 63 percent of the population is urban. There are 12 cities, 146 towns, 376 villages, and 298 rural municipalities in the province (Saskatchewan Economic Development, 1996).

Manitoba

Manitoba's population stood at about 1.14 million in 1995. This represents an increase of about 14 percent since 1971 (Table 3). Approximately 72 percent of the population is classed as urban (living in centres with greater than 1000 people). More than half the urban total live in Winnipeg, which together with Selkirk, accounts for about 60 percent of the population (Leslie Castling, personal communication).

Until 1941 the rural population component exceeded the urban. Since then, there has been a gradual shift of population from rural areas to the urban centres, particularly in the Prairie Ecozone This rural population decline has generally moderated proceeding northward and eastward, moving from the semi-arid grassland towards the moister parkland region. One notable exception to this trend, however, has occurred in the rural area around Winnipeg. The Lake Manitoba Plain experienced positive rural population growth of 7.1 percent between 1971 and 1991.

ECONOMIC TRENDS

Gross domestic product

All three Prairie Provinces experienced significant increases in Gross Domestic Product (GDP) during the 1970s and 1980s (Table 4). Alberta's growth rate significantly exceeded the national average, while Manitoba and Saskatchewan maintained national trends. Combined GDP for the Prairie Provinces in 1994 represented about 20 percent of the total GDP of Canada.

Table 3. Population and average annual growth rates, 1971-1995, Prairie Provinces and Canada (thousands)

Year	Manitoba	Saskatchewan	Alberta	Canada
1971	1001	934	1672	22 026
1981	1039	978	2304	24 900
1991	1113	1006	2601	28 120
1995	1138	1016	2747	29 606
% Change	13.7	8.8	64.3	34.4

Source: Statistics Canada, 1996, CANSIM, matrices 6367-6379

Table 4. Comparison of gross domestic product (in constant 1986 prices) , 1976-1994, Prairie Provinces and Canada (millions of dollars)

	Manitoba	Saskatchewan	Alberta	Canada
1976	12 000	12 034	40 119	371 688
1981	16 434	15 000	55 026	440 127
1986	18 408	16 874	56 553	505 666
1990	19 964	18 342	64 721	565 576
1994	17 508	18 067	70 560	532 464
% Change	44.7	50.1	75.9	43.3

Sources:
1971 -1990:
Alberta: Alberta Bureau of Statistics, Alberta Economic Accounts. 1990.
Saskatchewan and Canada: Saskatchewan Bureau of Statistics: Economic Review. 1993
Manitoba: Manitoba Bureau of Statistics, Manitoba Annual Economic Performance 1975-1991
1994:
Statistics Canada. Provincial Gross Domestic Product by Industrv.1984-1994, publication #15-203

Agriculture

Not surprisingly, the Prairies continue to dominate Canada's agriculture sector. For example, in 1991, this region contained 53 percent of all census farms with sales over $2500, 98 percent of wheat farms, 70 percent of other small grain farms, about 55 percent of cattle farms, and about 50 percent of mixed farms (Statistics Canada, 1993c). In spite of these statistics, however, agriculture in the Prairies has evolved considerably over the past couple of decades.

While the labour force engaged in Prairie agriculture has grown in absolute numbers during the 1981-1991 period, its share of the total labour force, and particularly its share of output has fallen dramatically. There is a large scale shift in orientation of the Prairie economy away from agriculture, particularly in Saskatchewan (Manitoba Bureau of Statistics, 1987, 1991; Saskatchewan Bureau of Statistics, 1983, 1993; Alberta Bureau of Statistics, 1990; Statistics Canada, 1994).

Significant changes in cropping practices are common in all three provinces (Statistics Canada, 1992; Alberta Agriculture, 1993). For example, the share of land in wheat production peaked in the mid-1980s, while land in canola and tame hay tended to maintain steady growth since the 1980s. Between 1991 and 1993, total wheat seeded in the Prairies fell as much as 15 percent while canola was on the rise. These changes reflect a general turn-around in prices in favour of oil seeds.

Some important relationships between crop production trends and climatic-soil zone can be identified. In the driest portion of the Prairies with light brown soils, spring wheat remains king, and actually grew in relative importance. There was some diversification into barley and canola and livestock production (greater conversion of unimproved land to improved pasture), and shifts out of crops such as winter wheat, oats and flax, but these changes are minor in relation to changes in spring wheat. In the more northerly, moist ecoregions, spring wheat is also dominant but there has been a more pronounced trend towards diversification into canola, barley and oats and greater reductions in summerfallow.

Manufacturing

The contribution to provincial GDP for the manufacturing sector increased only slightly in Saskatchewan and Alberta but increased significantly in Manitoba during the 1976 to 1994 period. While the manufacturing sector has contributed towards a proportionately larger share of Manitoba's economy since 1976, other sectors in Manitoba, such as agriculture, forestry and mining have declined substantially (Manitoba Bureau of Statistics, 1987, 1991; Saskatchewan Bureau of Statistics, 1983, 1993; Alberta Bureau of Statistics, 1990; Statistics Canada, 1994).
From 1971 to 1991 there was a general increase in value-added contribution of manufacturing in all three Prairie Provinces. The largest increase occurred in Alberta, followed by Saskatchewan

(Statistics Canada, 1993a). Manitoba's slower rate of growth over the period approximated the national growth rate. Growth rates were the highest during the 1970s but have moderated substantially during the past decade.

In 1992, the food, printing and publishing, and chemical manufacturing industries alone accounted for the bulk (about 40 percent) of prairie manufacturing value-added. Between 1981 and 1992, growing manufacturing industries in the Prairie provinces included electrical products (which doubled its share of total manufacturing value-added), wood (20 percent increase), chemical products (43 percent), transportation equipment (21 percent), printing and publishing (19 percent), the wood industry (20 percent) and food (9 percent) (Statistics Canada, 1993b). The largest declines were experienced in textiles and clothing, metal and fuel products, and machinery manufacturing.

Mineral industries

The contribution to provincial GDP for the mining sector increased significantly for Saskatchewan and decreased just as significantly for Manitoba from 1976 to 1994. Alberta had a modest increase in the proportion of its GDP derived from mineral industries. The growth in GDP in the mining sector is a consequence of the growth in coal, natural gas and crude petroleum (Manitoba Bureau of Statistics, 1987, 1991; Saskatchewan Bureau of Statistics, 1983, 1993; Alberta Bureau of Statistics, 1990; Statistics Canada, 1994).

There were increases in the total value of mineral production (including metals, structural materials and fuels) in Alberta and even more rapidly in Saskatchewan but declines in Manitoba from 1976 to 1991 (Alberta Bureau of Statistics, 1987, 1992). The value of production, in terms of the share of Canada's total, increased in Alberta and especially in Saskatchewan. Mineral production was most important in Alberta, followed by Saskatchewan and then Manitoba. By 1991 the value of mineral production in Alberta comprised approximately 46 percent of total Canadian mineral value.

The strength of Alberta's mineral industry can be attributed to its production of fuels, particularly petroleum. This is the result of expansion into the oil sands region of northern Alberta. Other minerals important to Alberta's economy include sulphur and structural materials such as sand and stone.

Manitoba's mineral industry is dependent on metals located in the Boreal Plains and Shield ecoregions and to a lesser extent on petroleum production from southwestern Manitoba. Nickel production is the most important mineral extracted but copper and gold also have become significant to Manitoba's economy.

Crude oil and potash deposits dominate Saskatchewan's mineral sector in terms of value of production. The crude oil industry increased by 132 percent between 1981 and 1994. The value of potash declined for several years over the same period but in 1994, it was 22 percent higher than in 1981. The value of uranium production during the same period increased by 58 percent. While natural gas increased 27-fold, it did this from a small base. Its relative contribution to the mining sector remains quite small (personal communication with Malcolm Wilson, Saskatchewan Energy and Mines).

Water

The major rivers in the Boreal Plain Ecozone include the Peace-Athabasca, Churchill and Lower Saskatchewan-Nelson. The Missouri, Assiniboine, Red, Qu'Appelle, Souris and North and South Saskatchewan flow through the Prairie Ecozone. The South Saskatchewan River Basin has the highest levels of water withdrawal and consumption.

Although water withdrawal in the Prairies is only 14 percent of Canadian withdrawals, total water use in the Prairie Ecozone amounts to 53 percent of Canada's total water consumption. This is because irrigation plays such a large role in total water use and is a large consumer of water due to evaporation and channel conveyance losses.

With the exception of large community water use, all categories of water use (small community, power plant and district irrigation projects) exceeded the growth of population since the 1950s. District irrigation experienced a 17 fold increase during the past forty years. Another dramatic increase in water use occurred in electrical generation (hydro and thermal power). The use of water for generation of electricity in the Saskatchewan-Nelson basin increased almost 4 percent annually, more than double the rate of population growth. At the same time, energy production has increased by almost 8 percent since 1950. These statistics suggest that there has been a trend towards water use efficiency (conservation) in electric power generation primarily due to improvements in technology.

The economic value of water in Canada is estimated at $16.3 billion annually and that of the Prairie Provinces at $2.2 billion (Table 5). These estimates do not include other important values such as riparian and aesthetic uses.

Forestry

Forests cover 38 percent of Saskatchewan, 40 percent of Manitoba and 58 percent of Alberta (Canadian Forest Service, 1993), with most of the forested land being located in the central and northern regions. The Prairie Ecozone only has about 3 percent of the total forest land of the three provinces.

Annual exports from the forest industry within the Prairie Provinces approached $2 billion in 1994, with $1.3 billion contributed by Alberta (Canadian Forest Service, 1991, 1993). In addition, more than 60 000 direct and indirect prairie jobs depended on this industry. This compares to $19.3 billion in exports nationally and about 880 000 people employed (Natural Resources Canada,1996).

In general, the area of land harvested by the forest industry between 1975 and 1993 increased in the Prairie Provinces at a rate higher than the national rate, largely due to the tremendous activity in Alberta. The area harvested in Alberta increased by almost 125 percent while Saskatchewan experienced a modest increase of about 5 percent. Manitoba, on the other hand, recorded a decrease of approximately 27 percent (Canadian Forest Service, 1991, 1993).

Table 5. Annual economic value of water, 1981, Prairie Provinces and Canada (millions of dollars)

	Prairies	Canada	Prairies as a percent of Canada
Withdrawal Uses			
Municipal[1]	636.2[2]	3628.0	17.5
Irrigated Agriculture	42.5	57.2	74.3
Thermal Power	16.2	169.4	9.6
Manufacturing	27.1	612.8	4.4
Total	722.0	4467.4	16.2
Instream Uses			
Hydro-electric[3]	995.6[4]	6553.4	15.2
Waste Assimilation	143.6	2272.0	6.3
Recreational Fishing[5]	330.5	2982.1	11.1
Commercial Fishing[6]	20.1	58.8	34.0
Sub-Total	1489.8	11866.3	12.6
TOTAL	2211.8	16,333.7	13.5

[1] median estimate
[2] Canada total pro-rated to Prairies on basis of population
[3] apply Zuker and Jenkins estimate, contained in Muller 1985
[4] values for Manitoba increased to include Alberta and Saskatchewan, on basis of annual hydro power generation
[5] median estimate
[6] value of freshwater catch, 1982

Source: adapted from R.A. Muller, “The Socio-Economic Value of Water in Canada”, Inquiry on Federal Water Policy, Research Paper Number 5, Ottawa, March 1985.

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CHAPTER 2

THE CLIMATES OF THE PRAIRIE PROVINCES

INTRODUCTION

The purpose of this chapter is to describe the past, present and possible future climatic regimes of the Prairie Provinces. This discussion will also include the classification of prairie climates and the present data collection network. The chapter will focus on two climatic parameters: temperature and precipitation. For information on a more complete range of climatic elements, the reader is referred to the Canadian Climate Normals (Environment Canada, 1993).

The climatic regimes of the Prairie Provinces are classified as cold temperate and sub-arctic. They range from dry continental type conditions in the southwest to near Arctic conditions in the northeast along the Hudson Bay coastline. Most areas of the Prairie Provinces receive their heaviest precipitation from storms fed by moisture flowing northward from the US Midwest. Average yearly temperatures are warmest in the south and coldest in the northeastern areas of the prairies. The western mountain ranges have a pronounced effect on precipitation patterns across the region and on winter temperature (Hare and Thomas, 1974).

CLIMATIC CONTROLS

Most of North America lies in a broad band of global circumpolar westerly winds. If it were not for the western North American mountain ranges, these mild and moist winds would flow eastward across North America much as they do in Europe. However, this Cordilleran barrier (normally referred to as the Rocky Mountains) has a pronounced effect on the climate of the Prairie Provinces. These mountain ranges deflect, block or greatly modify the incoming airmasses from the Pacific. Air masses which do cross the Rockies, lose much of their moisture and may undergo adiabatic warming as they flow onto the plains. These warm westerly winds are called Chinooks.

However, there are no physical barriers to airmasses invading from either the south or the north. Throughout the year, moist and warmer air from the US Midwest affects the southern prairies and occasionally leads to large precipitation events. During the winter, frigid air masses which form in the Arctic source region flow southward across the prairies. Such outbreaks occur in the wake of migratory disturbances and frequently produce blowing snow and/or high windchill conditions. While the region enjoys predominately sunny skies throughout the year, considerable fall and spring cloudiness occurs due to the oscillation of the migratory storm track across the region.

The extreme northeastern portion of the Prairie Provinces is strongly affected by its proximity to Hudson Bay. During the summer months, Churchill and other coastal communities are plagued by sea breezes off the cold water and/or ice covered surface of Hudson Bay. These sea breezes cause frequent cloudiness and cool temperatures. During the winter season, cold Arctic air accompanied by strong northwest winds often surges across this vegetation-sparse area causing dangerous windchill values and restricted visibilities in blowing snow.

The Prairie Provinces contain several very large lakes. These lakes have strong local climatic effects. Such effects include greater leeward cloudiness, a longer but cooler growing season, lake induced snowsqualls in the fall season and a complex local wind regime.

CLIMATE DATA

Although early fur traders and settlers recorded some information about daily and seasonal weather conditions on the Prairies, it was late in the nineteenth century before systematic detailed meteorological reporting became commonplace. Table 6 shows the starting dates for detailed meteorological reporting at a sampling of prairie locations with longer climatic records.

Table 6. Selected meteorological sites

Station	Observations commenced in:
Beaverlodge CDA	1915
Calgary	1884
Edmonton	1880
Fort Chipewyan	1883
Medicine Hat	1883
Swift Current	1885
Prince Albert	1884
Indian Head	1885
Regina	1883
Churchill	1884
Brandon	1883
Winnipeg	1872

Weather observations are normally taken at two types of stations. The first, and by far the most abundant type of station, is the ordinary climatic station. These recording sites are operated by trained volunteer observers who take daily, or twice daily, observations of temperature and precipitation. The second type are principal reporting stations operated by professional weather observers. The principal stations are frequently located at airports and they usually record a larger suite of weather elements. During the last decade, many of these principal stations have had automatic monitoring systems installed. All climatic data are quality controlled and archived according to World Meteorological Organization guidelines. As of 1996, there were approximately 500 ordinary climatic stations and about 200 principal stations operating in the Prairie Provinces.

A number of other agencies such as provincial agriculture, forestry and water departments, and private grain companies routinely collect climate information for their own purposes. To-date, these observations have not generally been combined with the data collected and archived by Environment Canada.

Climate data are summarized, tabulated and published by Environment Canada as the Canadian Climate Normals (Environment Canada, 1993) for such applications as agriculture, building codes, forest management, tourism, and so on. Normal climate values are 30-year averages, a period considered sufficiently long to account for the year-to-year variability of the climate. The current 30-year period spans 1961 to 1990. These publications are updated every ten years. They include ‘normals’ derived from data covering the 30-year period plus selected extrema based on the station’s entire period of record.

CLIMATIC REGIONS OF THE PRAIRIES

There are a number of well accepted methodologies for the classification of the world’s climates. Two of the more popular ones are the Koëppen and Thornthwaite classification systems. However, in this paper we will use the prairie subset of the Canadian climatic regions as developed by Gullet and Skinner (1992). Their classification of Canada’s climatic conditions resulted in 11 unique climatic regions. While six of these regions are represented on the Prairies (see Figure 2), our discussion will focus on the two main prairie climatic regions: prairie region and northwestern forest region. For a discussion of the other four adjacent climatic regions (South British Columbia Mountains, Mackenzie, Tundra and Northeastern Forest), readers are directed to other Canada Country Study chapter reports which cover these areas of Canada.

PAST CLIMATE

Instrumental climate data from the Prairie Provinces rarely extends more than a century, and therefore is insufficient to detect trends longer than a few decades. Ecological monitoring data for this region tend to extend for even shorter intervals (several decades at best) and often provide information that has high variability, making it difficult to assess whether trends are ‘noise’, reflecting inherent variability within the systems being monitored, or are responding to more fundamental environmental changes. In contrast, recent paleoenvironmental work on the Canadian Prairies and elsewhere has clearly shown a sequence of long-term, broad-scale climatic trends, roughly synchronous over wide areas, and their associated ecological responses. The paleoenvironmental record, therefore, provides the context against which to examine traditional ecological monitoring data.

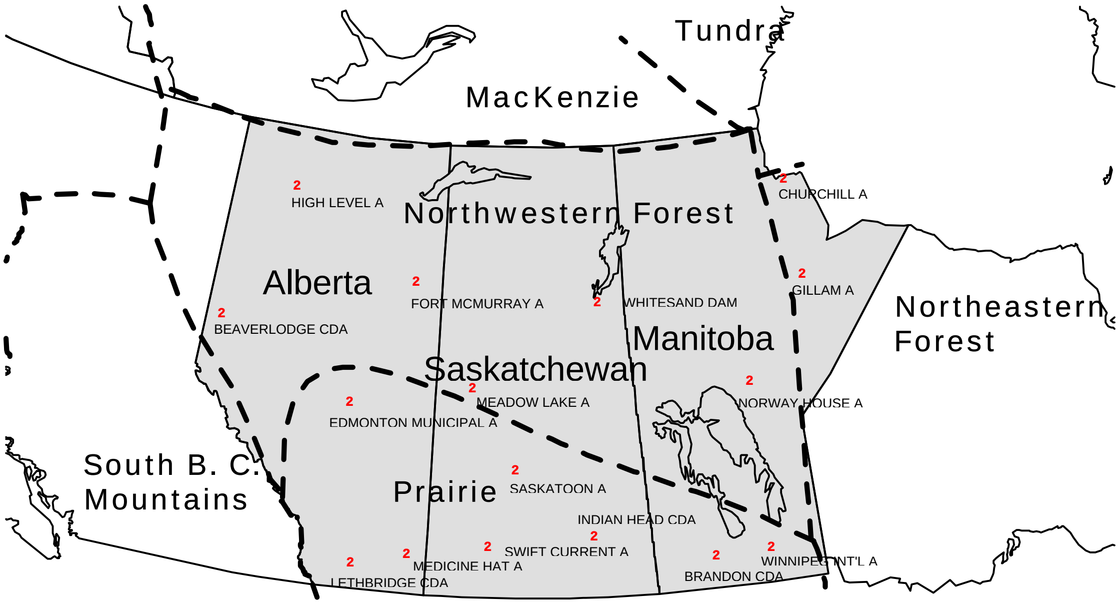
Much of the knowledge of postglacial

environments on the Prairies Provinces has been derived from the study of pollen records recovered from lakes and wetlands. There are about 100 paleoenvironmental records available, with more from Alberta than the other prairie provinces. Most records have been obtained from the southern boreal forest, the parkland and mountain regions. Recent years have seen a determined effort to obtain data from grassland regions as part of the Geological Survey of Canada's Palliser Triangle Global Change Project (Vance, 1997).

At a very generalized level, paleoenvironmental records for the Prairies concur in showing a broad three-part division of the postglacial. The early part (prior to about 9000 years BP), for which there are comparatively few records, shows a sequence of rapid vegetation changes that reflect postglacial migration of plants into the region, soil development, and landscape response to postglacial conditions, all of which tend to blur the climate signal. Between around 9000 and about 6000 BP, most records show evidence of aridity, increased salinity and higher than present temperatures, with the Prairie grasslands probably extending up to about 80 km farther north than their present range. This interval (which is time transgressive across the Prairies) is known as the Hypsithermal, and likely serves as the best analogue for conditions predicted by GCMs under a doubling of CO_2 concentrations. After about 6000 BP, increased moisture and probably cooler temperatures are inferred from rising lake levels, decreased salinity, southward advance of the boreal forest margin, and the inception of peat accumulation in central Alberta. This cooler, wetter interval resulted in renewed ice accumulation in the Canadian Rockies which led to the first well-marked Neoglacial advance around 4000 BP. A series of ice advances have occurred in the last 4000 years, although most glaciers show their maximum advances in the last few centuries, during the Little Ice Age.

These general climate changes include considerable smaller scale variability. For example, within the last millennium there were two broad climate phases: the Medieval Warm Period, ending around the 12th century, followed by the Little Ice Age. Within each of these intervals, even smaller scale climate trends, on the order of decades or less, have been detected. For instance, during the late 19th century, the era of EuroCanadian exploration and settlement of the grasslands, tree ring records have shown sequences of drought years, interspersed with wetter intervals. A comprehensive listing of past literature and current research on the use of proxy records in determining the postglacial climate of the prairie provinces, as compiled by D. Sauchyn, is attached to this volume as Appendix I.

Figure 2. Prairie Provinces showing climatic regions and climatological stations discussed in this chapter (after Gullett and Skinner, 1992)



PRESENT CLIMATE

Northwestern forest region

Geography and climatic classification

This climatic region essentially covers the northern portion of the Prairie Provinces. Land elevations range from sea level on the Hudson Bay coastline to above 1000 m along the Alberta foothills. The predominant vegetation in the region are open and closed stands of coniferous forest. However, along the southern edge of the northwestern forest region, the land use is a mixture of agricultural lands and forest stands. Here the forest is a mix of deciduous and coniferous tree species.

The climate classification of the northwestern forest region contains sub-Arctic and cold temperate climatic zones. The region is characterized by long, cold winters and short, semi-humid summers. The northwestern forest is well removed from major climatic control features such as the Pacific Ocean and Rocky Mountains which results in rather homogeneous climatic conditions except for its southward extension into western Alberta.

Temperature

Figure 3 illustrates the seasonal temperature regimes for locations across the northwestern forest region. Mean daily temperatures in January are in the -12 to -25°C range, while summer mean daily temperatures are in the +15°C range. The summer frost-free period ranges from 70 to 110 days.

Precipitation

Annual precipitation in the northwestern forest region ranges from 400 to 550 mm. Table 7 gives the seasonal rainfall (in mm) and snowfall (in cm) for the same station grouping as in Figure 3. Most of the precipitation falls during the summer and autumn seasons either as showers, or as rain or snow associated with migratory weather disturbances. The frequent outbreaks of cold dry Arctic air bring only light precipitation to the region. A continuous winter snow cover lasting 5 to 6 months is normal.

The vegetative growth in the northwest forest is generally temperature limited in the north and precipitation limited in the south (Singh and Wheaton, 1990; Hogg, 1994).

Figure 3. Daily temperature variation (extreme maximum, mean maximum, mean minimum and extreme minimum) by season for locations in the Northwestern Forest Climatic Region

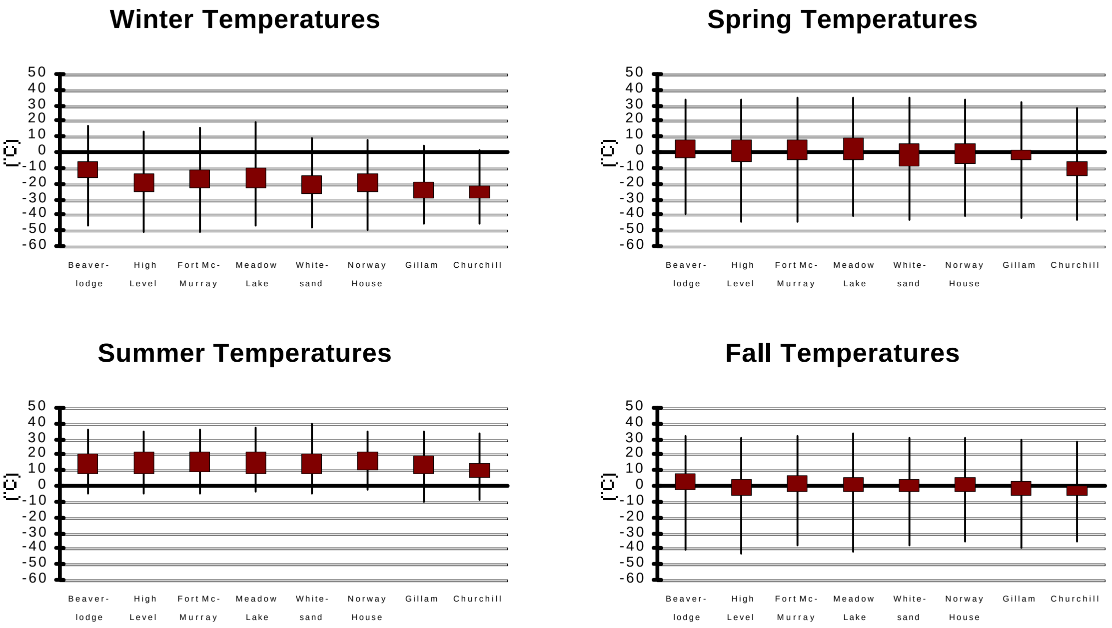


Table 7. Seasonal rainfall (mm) and snowfall (cm) for locations in the Northwestern Forest Climatic Region (1961 - 1990 data)

		Station Name							
Season	**Weather Parameter**	**Beaver-lodge**	**High Level**	**Fort McMurray**	**Meadow Lake**	**White-sand**	**Norway House**	**Gillam**	**Churchill**
Winter	Rain (mm)	1.7	0.9	2.5	0.1	0.2	0.4	0.0	0.2
(DJF)	Snow (cm)	101.0	74.6	79.0	46.4	76.5	84.3	77.2	59.3
Spring	Rain (mm)	42.7	43.6	46.1	38.7	44.3	48.8	35.5	15.9
(MAM)	Snow (cm)	42.6	38.6	42.6	29.5	46.7	49.7	71.6	61.3
Summer	Rain (mm)	202.7	180.7	214.7	179.0	217.0	213.2	210.5	151.4
(JJA)	Snow (cm)	1.3	0.0	0.0	0.0	0.3	0.0	2.4	4.2
Fall	Rain (mm)	61.7	49.6	71.0	47.4	89.9	82.5	66.7	67.8
(SON)	Snow (cm)	42.3	44.5	50.5	24.6	53.6	54.4	70.8	75.2
Annual	Rain (mm)	308.8	274.8	334.3	265.2	351.3	344.9	312.7	235.3
	Snow (cm)	187.2	157.7	172.1	100.5	177.1	188.4	222.0	200.0

Prairie region

Geography and climatic classification

The Prairie region encompasses the southern portions of the three Prairie Provinces (see Figure 1). Elevations greater than 1500 m are found in the extreme western portion of the region and descend, in a series of steps, eastward reaching about 250 m by the Red River Valley in southern Manitoba. The generally flat lands are frequently broken up by outcroppings of low hills and steep-sided river valleys. The predominant land use is agriculture with approximately 70 percent of the land under cultivation. (Environment Canada, 1991)

The climate of the prairie region is classified as cold temperate and is characterized by warm summers and cold winters. The western portion of the region is strongly affected by the Rocky Mountains. Farther east, the localized effects of the mountains are gone but westerly winds still yield relatively little precipitation because of the rain shadow effect. The area receives an abundance of sunshine throughout the year (Environment Canada, 1993).

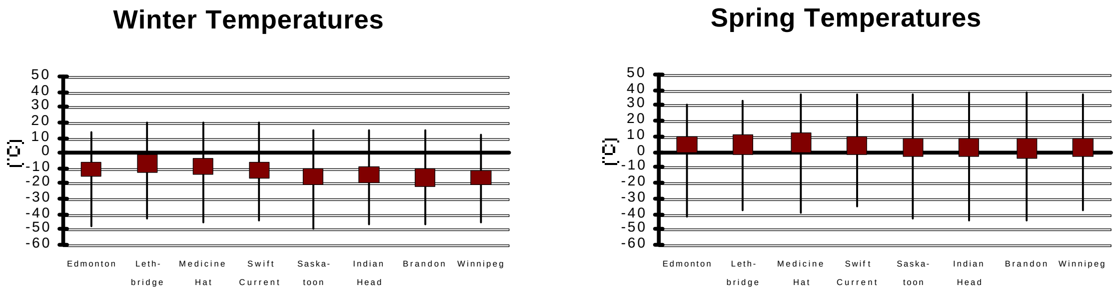
Temperature

Figure 4 illustrates the seasonal temperature regimes for selected locations in the Prairie climatic region. Mean annual temperatures range from +2 to +6°C. Daily mean temperatures vary from -6 to -16°C in January to about +18°C in the summer months. The summer frost-free period ranges from 95 to 125 days.

Precipitation

Annual precipitation in the prairie region ranges from 300 to 500 mm with the driest conditions in the southwest and the higher amounts towards the north and east. Table 8 gives the seasonal rainfall (in mm) and snowfall (in cm) for the same station grouping as in Figure 4. Most of the summer precipitation falls as showers, while precipitation in the other seasons is most often associated with migratory disturbances or intrusions of moist air from the south. Although the continuous snow cover period in southwestern regions is quite variable from year-to-year, northern and eastern regions can expect about 4 to 5 months of continuous snow cover.

Figure 4. Daily temperature variation (extreme maximum, mean maximum, mean minimum and extreme minimum) by season for locations in the Prairie Climatic Region



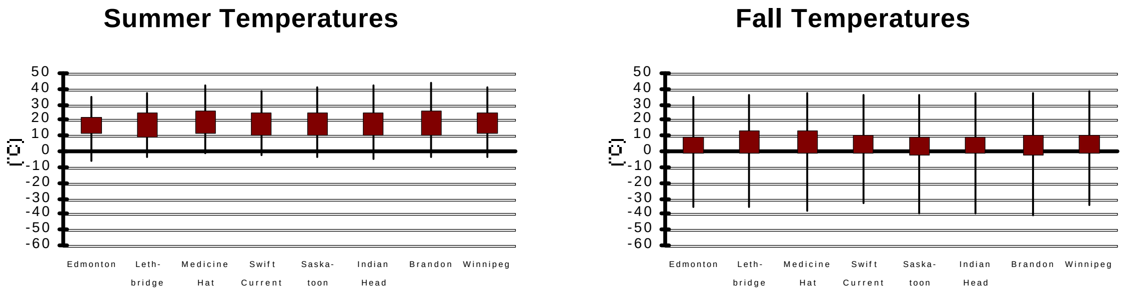


Table 8. Seasonal rainfall (mm) and snowfall (cm) for locations in the Prairie Climatic Region (1961 - 1990 data)

		Station Name							
Season	**Weather Parameter**	**Edmonton**	**Leth-bridge**	**Medicine Hat**	**Swift Current**	**Saska-toon**	**Indian Head**	**Brandon**	**Winnipeg**
Winter	Rain (mm)	3.7	1.2	1.5	2.7	1.5	1.2	1.2	2.3
(DJF)	Snow (cm)	70.7	69.4	52.7	59.8	53.8	70.8	60.9	59.8
Spring	Rain (mm)	52.4	63.5	55.4	50.3	54.1	68.0	76.9	90.1
(MAM)	Snow (cm)	33.3	49.4	31.6	41.4	27.5	37.1	30.8	30.6
Summer	Rain (mm)	241.1	148.9	127.9	153.9	158.2	183.0	212.9	231.1
(JJA)	Snow (cm)	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0
Fall	Rain (mm)	52.1	46.9	45.2	40.5	39.9	59.0	74.1	80.8
(SON)	Snow (cm)	25.6	31.1	24.0	26.6	24.2	27.0	16.3	24.3
Annual	Rain (mm)	349.3	260.5	230.0	247.4	253.7	311.2	365.1	404.3
	Snow (cm)	129.6	150.1	108.3	127.8	105.5	134.9	108.0	114.7

CLIMATIC CHANGE

To determine whether the climate is changing over time, it is necessary to distinguish between short term fluctuations and long term trends in the climate record. Only by studying the climate data over a sufficient period of time is it possible to detect climatic changes such as a warming or cooling trend.

The United Nations Framework Convention on Climate Change (FCCC, 1992) defines climate change as, “a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods”.

The Intergovernmental Panel on Climate Change (IPCC) has examined the long term record and has determined that the global average surface temperature has increased by about 0.5 °C over the last century (IPCC, 1995). This warming has not been uniform but has been greatest over the continents at the middle latitudes of the Northern Hemisphere.

Yearly mean temperature anomalies for the recorded period of observations for the Northwestern Forest and the Prairie climatic regions are plotted in Figure 5. Despite the year-to-year fluctuations in the data, the overall trend lines indicate a warming trend.

Gullett and Skinner (1992) examined the data from more than 100 Canadian climate stations with periods of record dating back to about 1895 to determine the occurrence or non-occurrence of a warming trend over Canada. This work began with the creation of the climate regions described earlier in this chapter. Departures of the long term temperatures from 1951 to 1980 Normals were obtained for each climatic region and plotted in a time series to determine any evidence of climate change. The portion of this study that pertains to the Prairie Provinces is presented in Table 9.

To be statistically significant, a clear trend must emerge from the highly variable year-to-year temperature measurements for a particular region. Gullet and Skinner (1992) found that the trends for the Northwestern Forest and the Prairie climate regions are statistically significant (at the 95% confidence level). They also noted that the temperature changes over the past century have shown three distinct phases: a warming trend from the late 1890s to the 1940s, followed by a cooling trend from the 1940s to the 1970s, and a resumption of a warming trend in the 1980s.

Figure 5. Yearly mean temperature anomalies and trend lines, for the period 1895 to 1996 for the Northwestern Forest and the Prairie climate regions

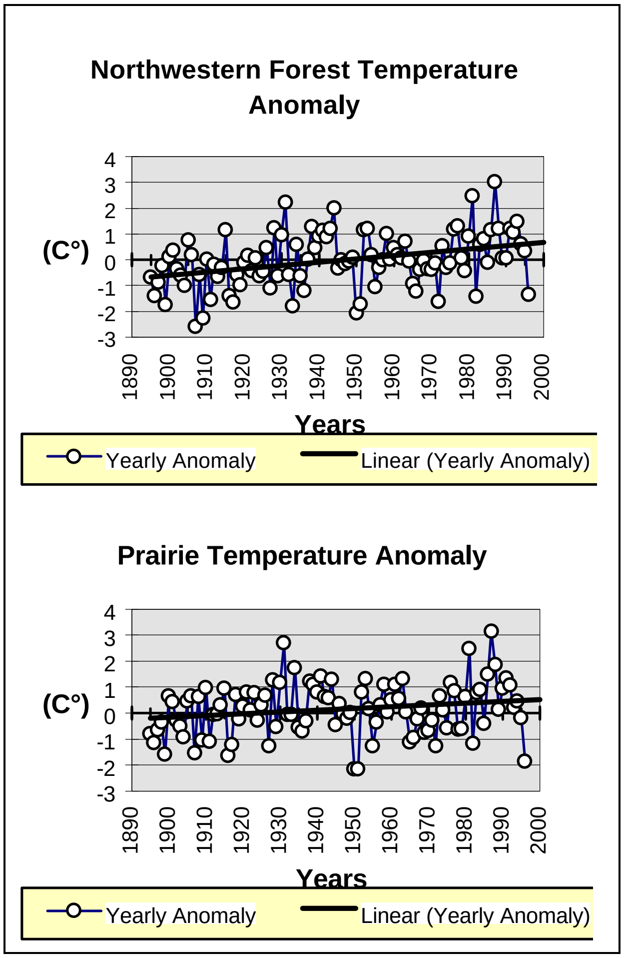


Table 9. Departures of the long term mean annual temperature (based on 1895-1991 data), from the 1951 to 1980 normals, for the two primary climatic regions in the Prairie Provinces. (Gullett and Skinner, 1992)

Climatic Region	Temperature Change	Statistically Significant (at the 95% confidence level)
Prairies	+0.9 °C	Yes
Northwestern Forest	+1.3 °C	Yes

In recent years, concern has been expressed that the world may be on the brink of unprecedented climate change due to rising levels of greenhouse gases in the atmosphere (IPCC, 1995). Considerable research has been dedicated to the development of General Circulation Models (GCMs). These are physically-based computer models designed to simulate the radiative effects of various concentrations of greenhouse gases on the global climate. There are many reputable GCMs, each producing somewhat different climate change scenarios depending on their unique mathematical and physical formulations. The fact that different GCMs produce different results, particularly on a regional scale, is an indication of the uncertainty inherent in the ability of these models to precisely cast future climatic conditions. However, these same models predict similar future global scenarios. (IPCC, 1995)

Recent GCM estimates of the projected rise in long term global average annual surface temperature are between 1.0 and 4.5 Celsius degrees with a simulated doubling of CO_2 concentrations (IPCC, 1995). On the sub-continent scale there is greater inter-model uncertainty in the predicted results and thus it is not possible to know with confidence the fine details of how the climate will change regionally.

Table 10 summarizes the projected changes in seasonal temperature and precipitation produced by three different GCMs for the two main climatic regions of the Prairie Provinces for the latter half of the twenty-first century. The lower and higher values in each of the categories represent the spatial variability in the projected changes in temperature and precipitation. The temperature values are the amount that the predicted temperature differs from the present ‘normal’ temperature. The precipitation values are the percentage change that the predicted value differs from the present ‘normals’. Although the temperature predictions are quite variable, it is important to note that in all cases they are positive. In general, precipitation is harder to model and therefore these predictions show greater variability than those for temperature.

The three models are: the CCC GCMII, prepared by the Canadian Centre for Climate Modelling and Analysis (Boer et al., 1992); the GFDL GCM from the Geophysical Fluid Dynamics Laboratory at Princeton University (Manabe et al., 1991 and 1992), and NASA’s GISS GCM produced by the Goddard Institute for Space Studies (Russell et al., 1995; Hansen et al., 1983). The GFDL and the GISS GCMs are transient models whose CO_2 is increased by 1 percent per year until CO_2 concentrations are doubled. These atmospheric models are coupled to fully circulating ocean models in order to simulate the oceans' effect on the climate as it changes very gradually over time. The CCC GCMII is called an equilibrium model whose results represent the full response of the atmosphere and ocean to an instantaneous doubling of CO_2 concentrations. More information concerning these models and their application may be found in the references.

The expected timing for a doubling of CO_2 depends on our assumptions about the future rate of greenhouse gas emissions as well as the base period chosen. When used in conjunction with the 1951-80 or 1961-90 Normals and a standard IPCC emission scenario, IS92a (IPCC, 1995), the valid period for the climate change projections shown here are for the latter half of the twenty-first century. However, when the contributions of all the greenhouse gases are included the "equivalent" doubling of CO_2 occurs earlier.

Table 10. Predicted seasonal temperature (C°) and precipitation (%) changes for Prairie Province climatic regions by three General Circulation Models for a doubled CO2 atmosphere

		PRAIRIE					**NORTHWESTERN FOREST**			
		Temperature Range		**Precipitation Range**			**Temperature Range**		**Precipitation Range**	
Season	**Model**	**Lower**	**Higher**	**Lower**	**Higher**		**Lower**	**Higher**	**Lower**	**Higher**
WINTER										
(DJF)	CCC	5.5	8.0	-10	35		4.5	7.0	0	30
	GFDL	2.5	3.5	5	20		2.5	4.0	5	20
	GISS	2.0	2.5	10	25		2.5	3.0	0	15
SPRING										
(MAM)	CCC	5.0	9.0	20	50		3.0	5.0	-5	25
	GFDL	2.5	3.0	5	15		2.5	3.5	5	15
	GISS	1.5	2.0	5	15		1.5	2.0	5	20
SUMMER										
(JJA)	CCC	3.5	5.5	-15	0		3.5	5.5	-15	10
	GFDL	2.5	3.0	-15	10		2.0	2.5	-10	15
	GISS	0.5	1.0	-10	15		0.5	1.0	10	40
FALL										
(SON)	CCC	2.5	3.5	0	30		2.5	3.5	5	30
	GFDL	3.5	4.0	-5	10		3.5	4.5	-5	10
	GISS	1.5	2.5	-15	10		1.5	2.5	0	20

Legend: CCC is the Canadian Centre for Climate Modelling and Analysis
GFDL is Princeton University's Geophysical Fluid Dynamics Laboratory
GISS is NASA's Goddard Institute of Space Studies

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CHAPTER 3

REGIONAL CLIMATE SENSITIVITIES

INTRODUCTION

Before impacts of possible future climate change scenarios can be addressed, which is the focus of Chapter 4, it is necessary to assess the sensitivity of ecological and socioeconomic systems in the Prairie Provinces to *climatic variability*. Climate sensitivity can be defined as the degree to which a system will respond to climatic conditions, generally a given change in temperature and precipitation. This knowledge of current and past climates is derived from climatological measurements, historical observation and paleoclimatic research.

By answering the question, How will a system respond to given changes in climate? we can begin to evaluate its sensitivity, adaptability and vulnerability to future climatic changes. This chapter addresses this question.

AGRICULTURE

While there are many aspects of climate to which prairie agriculture is vulnerable, drought can inflict the most extensive damage. During this century the Canadian Prairies have experienced two periods of higher than normal temperature and abnormally low precipitation: the 1930s and the 1980s.

Furthermore, proxy climate data demonstrate that drought intervals of the past century have been relatively minor compared to episodes prior to European settlement. The most severe drought of the past 500 years in the prairies occurred between approximately 1791 and 1800 (Case and MacDonald 1995). During earlier warm intervals, as recently as 1000 years ago, drought intervals of far greater severity than observed in the instrument record were frequent (Vance et al., 1992).

The southern Prairies were economically the hardest hit by the 1930s drought. It has been estimated that between 1933 and 1937, rainfall was only 60 percent of normal, devastating livestock and crop production (Phillips, 1990). Wheat yields declined 32 percent and corn yields dropped as much as 50 percent. Low crop yields year after year led to the failure of about 200 000 farms and the migration of an estimated 300 000 people from the region (Phillips, 1990). These disasters were a consequence of land-management practices that were associated with European techniques which came with the settlers. The practices of single-wheat farming, dustmulching, mechanisation, and cultivating fallow land, exacerbated wind erosion. Only after the out-migration had occurred and the climate had returned to more normal levels of precipitation, did management practices such as the adoption of conservation tillage techniques and risk management programs come into effect (Rosenzweig and Hillel, 1993).

The drought in 1986-1988 was more severe primarily because of higher mean temperatures. As characterized by Arthur and Chorney (1992), the drought period in the 1980s was significant because of its intensity, duration, areal extent and effects. The warm and dry fall weather persisted into the winter of 1987-1988. In Alberta and Saskatchewan less than 50 percent of normal precipitation fell during the growing season. The mean temperature was 2-4°C above normal in March, April and May. The summer of 1988 was hot, dry and dusty, with mean temperatures 4-7°C above normal, and became the hottest summer on record for many localities. The combination of heat and insufficient moisture caused severe droughts in southern Manitoba, south central Saskatchewan and south eastern Alberta.

The effects on crop production and livestock were substantial across the Prairies, although Alberta faired relatively better than Saskatchewan and Manitoba (Arthur and Chorney, 1992). Production of the seven major grains was 29 percent less than in the previous year, and production of western

Canada's four major specialty crops was down by 40 percent. Inventories were reduced significantly, and while marketing volumes were relatively high due to favourable prices and the depletion of older stock, export losses were estimated at $4 billion (Phillips, 1990). Weed growth was one of the major problems. The heat caused rapid growth and poor herbicide performance. Grain seeds were affected by poor germination and growing conditions (Arthur and Chorney, 1992). Despite the adverse effects on germination, however, the crop quality actually increased in 1988, due to dry conditions during the growing and harvest seasons. The indirect effects through insects and diseases also changed.

Livestock production also was severely affected through the effects on feed, from dust storms, and the lack of suitable pasture land due to drought or grass fires. Ranchers were forced to move their herds to areas where feed and pasture were more plentiful. In Manitoba, cattle breeders moved their cattle to northern areas, whereas in the US the drought pushed the herds south.

Cattle producers and grain farmers were helped by a number of support programs. A combination of crop insurance and special drought assistance, for example, paid out over $1.3 billion to Prairie farmers, an amount also supplemented by provincial support programs. Despite this support, Manitoba showed net farm income losses of 50 percent and Saskatchewan 78 percent (Arthur and Chorney, 1992). Due to the effects of the drought, and previous years of low prices, an estimated 10 percent of farmers and farm workers left the agriculture sector in 1988 (Phillips, 1990).

FOREST ECOSYSTEMS

Many aspects of the boreal forest are either directly or indirectly related to climate. Flowering, pollination, seed formation, germination, and competitive success of seedlings are particularly climate sensitive. Other sensitivities include soil nutrient status, hydrology, community dynamics, structure and function (Singh and Wheaton 1991).

The circumpolar boreal forest is often considered to be predominantly temperature limited. The western interior Canadian forest, however, is thought to be temperature limited at its northern edge and moisture limited at its southern boundary (e.g., Singh and Wheaton 1990, Hogg 1994). It also has a greater fire hazard than the eastern Canadian boreal forest. Risk factors such as fire, wind, drought, insects and disease play key roles in the health and growth of the boreal ecosystem (e.g. Wheaton et al*.* 1987).

The structure and function of the boreal forest ecosystem are more clearly dependent on climate than those of many other ecosystems (Wheaton et al., 1987). For example, net primary productivity rises with both temperature and precipitation. Trees growing under different climatic regimes have different growth rates and productivity. Climate has considerable influence on growth and disturbance factors.

The present geographic distribution of vegetation zones is largely affected by climate at a global scale and at scales such as that of the boreal forest (e.g., Holdridge 1964, Tukhanen 1980). At present, the southern boundary of the western Canadian boreal forest meets the aspen parkland zone. This zone is characterised by grassland with patches of trembling aspen (*Populus tremuloides* Michx.). The northern boundary of the forest is a transition to a tundra zone.

Climate lessons from the past

Most instrumental records in western Canada provide a relatively short perspective, usually less than 100 years, on climatic variability, and by themselves form an inadequate basis for forecasting the severity and duration of future climatic extremes. A much longer perspective on the magnitudes and frequencies of extreme climate, such as drought, is available from proxy paleoclimatic data. Some of the best proxy data are indicators of lake level change and tree growth variation. Lake basin forests provide evidence of both.

The reconstruction of pre-settlement climate is based primarily on the statistical relationship between ring width and meteorological data from the post-settlement period. Other tree ring parameters include wood density, the concentration of stable isotopes (Gray and Thompson, 1977, 1979), and widths of the latewood and earlywood in each annual ring. Over much of the Interior Plains, including the southern boreal forest (Larsen and MacDonald, 1995), tree growth is limited by the availability of water. Thus a record of precipitation variability can be derived from climatically-sensitive trees, those growing in well drained substrates where a continuous supply of water generally is not available (Stockton and Meko, 1975; Meko, 1992).

In western Canada, dendrochronology has been largely confined to the montane and boreal forests (Case and MacDonald, 1995; Luckman and Innes, 1991). An investigation of fire and insect infestation frequency in the jack pine forests of Manitoba (Gill, 1930) was the first Canadian study to use ring-width data and cross-dating techniques to develop a tree-ring chronology.

Case and MacDonald (1995) constructed a 487-year record of annual precipitation from *Pinus flexilis* (limber pine) in the foothills of southwestern Alberta. They determined a drought return period of 30-50 years, which has not changed appreciably over the past five centuries. Severe drought in the 1790s in their record, was previously identified by Sauchyn and Porter (1992) from the Cypress Hills. In Manitoba, Nielsen (Manitoba Geological Survey, personal communication, March, 1997) has established an oak chronology back to 1660 and collected oak from the deposits of the Assiniboine and Red Rivers that dates to > 2000 years BP. Although a belt of aspen parkland extends across the prairie provinces, much of the original aspen poplar (*Populus tremuloide*s) was removed for crop production.

Palynology, or the study of plant pollen, is another proxy technique for interpreting the sensitivity of vegetation to past climates. Pollen studies in the prairie provinces have led to the acceptance of a spruce-dominated postglacial forest and shifting of the prairie ecozones. The postglacial forest migrated northward with the retreat of the Laurentide ice sheet and became established as the boreal forest.

From an instrumental record perspective, twenty years of biophysical data for the Experimental Lakes Area of northwestern Ontario indicated many changes that may be comparable to those expected in the future (Schindler et al., 1990). While the study area is outside the one considered here, it is close enough to warrant attention. The period of record has been one of mostly continous warming and increasing frequency of drought. The rising air and lake temperatures and lengthened ice-free season also caused evapotranspiration to increase and runoff to decrease. Large areas of forest cover were lost to fire and were associated with an increase in wind speed. Several ecological trends also were measured. Populations and diversity of phytoplankton increased in one lake, but primary biomass production showed no evident trend. Summer habitats for cold stenothermic organisms such as trout and opossum shrimp decreased.

The droughts of the 1980s extended northward into the northwest forest (Wheaton and Arthur 1989). Forest effects included lower than normal annual wood volume increments (estimates), higher than normal seedling mortalities, tent caterpillar and spruce budworm outbreaks and considerable fire damage and fire suppression costs (Wheaton et al., 1992*b*). Tree ring analyses indicate that radial growth of aspen is reduced by at least 90 percent during a severe drought (Hogg and Hurdle, 1995).

Hogg (1994, 1996) showed that the southern limit of the western boreal forest corresponds most closely with climatic moisture regimes (annual precipitation minus potential evapotranspiration [P-PET]). Thermal characteristics of climate (e.g., growing degree-days) showed an inconsistent relationship with the southern limit (Hogg, 1994). This close relationship for the southern boundary suggests that it is likely governed, directly or indirectly, by climatic moisture deficiency and drought occurrence. One of the most likely explanations of this control is that conifer regeneration from seed is restricted in drier climates. Even in naturally forested regions, moisture deficiency was found to frequently reduce the germination rate, photosynthesis, and survival of conifer seedlings. Coniferous forests and peatland development are generally limited to areas where annual precipitation is greater than potential evapotranspiration.

How drought tolerant are boreal species? This question has implications for changes in the southern parts of the zone. Aspen occurs naturally in drier areas than conifer species. However, high mortality of aspen groves has occurred during past prairie droughts of 1961 (Zoltai et al., 1991 in Hogg, 1994) and of the 1980s. Also, mature planted conifers in the aspen parkland seem to have suffered less during recent droughts (Hogg p. obs. in Hogg, 1994). The more southerly distribution of aspen is likely a result of its vegetative mode of regeneration. The drought tolerance of different species, in terms of regeneration and growth, for example, are important questions that require further attention, even with the present climatic probability of droughts.

Disturbances

"Wildfire is the driving successional force in the boreal forest and has remained so despite fire suppression activities and extensive harvesting. Insects and diseases also cause extensive damage" (Hall, 1995).

Disturbances such as fires and insects are key factors in the health and growth of existing forests as well as in the success of future restocking efforts (IPCC WG II, 1996). Tree mortality in the boreal shield ecozone is caused by natural factors such as insects, diseases, and storms. Annual tree mortality in the boreal shield ecozone ranges from nil to 2.5 percent. The highest mortality rates occur in trembling aspen and balsam fir and are caused by damage from outbreaks of the forest tent caterpillar, the large aspen tortrix and the eastern spruce budworm. Mortality in the boreal plains ecozone has been 2 percent or less annually since 1985. In this ecozone, mortality is mostly caused by natural thinning, insects, and diseases. No signs of pollution damage have yet been observed in 70 boreal ecozone plots studied by the Canadian Forest Service (CFS, 1996*a*).

Carbon budget

"Forests play an important role in the global carbon cycle, fluctuating between being a sink and source for CO_2. They absorb and store CO_2 during growth cycles, and they release CO_2 to the atmosphere during respiration, decomposition and burning. The boreal forest is one of the world's largest ecosystems and is the dominant forest region in Canada, Alaska and Russia. Canadian scientists are working with scientists from the United States [USA] and other countries to improve our understanding of the role of the boreal forest in the global carbon cycle and the interaction between forests and the Earth's climate." (CFS, 1996:44)

Boreal, tundra, and subarctic (high-latitude) terrestrial biomes cover about 25 percent of the Earth's land surface, and contain about one third of the global terrestrial ecosystem total carbon. Plausible changes in vegetation structure may result in both positive and negative climatic feedbacks. Some of the more immediate and transient feedbacks include carbon dioxide release from drier organic soils and methane releases from melting permafrost (Price and Apps, 1995).

Krankina and Harmon (1995) write that "One of the most important questions facing ecologists today is the role of the biota in the global carbon cycle." We still do not understand the current role of forests in controlling the global carbon cycle. This uncertainty is reflected in the fact that 20 to 50 percent of the annual fossil fuel carbon cannot be accounted for and that forests are described as both sources and sinks, depending on the study and period considered.

Forest land management affects the net exchange of carbon between the atmosphere and the forest ecosystem. The types of management implicated include harvesting, silviculture, site preparation and forest products utilisation (Kurz and Apps, 1993). Krankina and Harmon (1995) found that intensive forest management including short harvest rotations, thinning and wood salvage reduces dead wood carbon stores from 5 to 40 percent of the potential level of undisturbed old-growth boreal forests (northwestern Russia) and that natural disturbance increases the dead wood carbon pool by a factor of two to four.

Forest dynamics as affected by climate and other factors could significantly affect the carbon content of the atmosphere. Kurz and Apps (1995, 1996) analysed the range of responses of the forest carbon budget to different management options, including reducing disturbance rates, accelerating regeneration of disturbed areas, and converting non-stocked forest land to productive stocked forests. Changes in the area disturbed (mostly by wildfire and insects) greatly affect biomass and soil carbon dynamics and therefore the annual net carbon exchange with the atmosphere. Disturbance areas have greatly increased in the 1970s and 1980s as compared to the previous 50 years. The five-year average of the area disturbed annually in the Canadian boreal forest was more than twice as high, at 3.9 Mha y^{-1}. Reducing the rate of disturbances increases the rate at which forests switch from a carbon source to a sink, and vice versa. Their results showed the estimated 50 year carbon budget of the six management options ranged from a net source of 1.4 Pg carbon to a net sink of 9.2 Pg carbon.

ENERGY

Extreme years or sets of years provide good "experiments" to assess the sensitivity of sectors to climate. For example, energy and climate variations for the 1960 to 1989 period were presented by Wilson (1990) for the Saskatchewan Climate Advisory Workshop. He focused on power consumption and sources as affected by climatic variability. Time series of heating and cooling degree-days, energy requirements, peak load, electric heat load, air conditioning load, irrigation load, hydroelectric generation, fuel costs and reservoir levels were provided. However, relationships of climate with loads and generation types were not developed.

The time series of heating and cooling degree-days (Figure 6) warrant further analysis. Although there is considerable year to year variability over the 1960 to 1989 period, the overall trends of decreasing heating degree-days and increasing cooling degree-days are evident. The greater variability of the 1980s as compared to the 1970s is also noticeable. The extreme high cooling degree-days accumulated in 1961, 1984 and 1988. The extreme low values for heating degree-days occurred in 1987, 1981 and in 1976.

The environmental and economic sensitivities of the 1988 drought, with an emphasis on Manitoba and Saskatchewan, were documented by Wheaton and Arthur (1989; summarized in Wheaton et al., 1992, Climatological Bulletin). The highlights are:

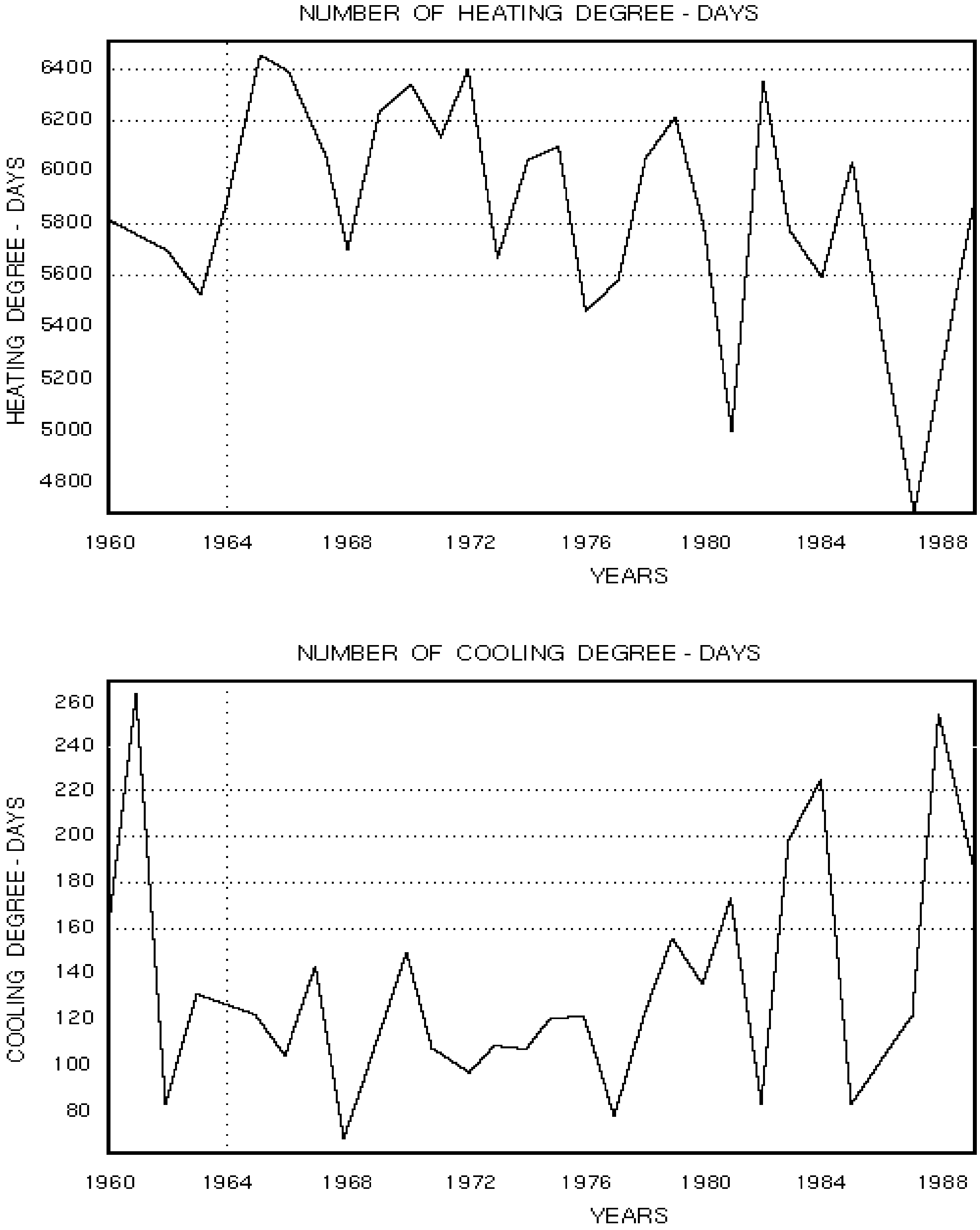
Manitoba:

- hydroelectric power comprised 94 percent of all power generation in 1988, down 4 percent from "normal" years.
- a net expense of $18.5 million was accumulated by Manitoba Hydro by the end of the 1987 to 1988 fiscal year. Drought was considered to be the major contributing factor.
- costs of increased fossil fuel consumption and power purchases from other sources was almost half of the increase in expenses (before finance charges).
- hydroelectric generation dropped from a record 24 billion kWh in 1986/87 to only 18 billion kWh in 1987/88; and it dropped further to 15.2 billion in 1988/89 (a 36.7 percent drop between 1986 and 1988).
- export sales dropped to $31 million in 1988/89; a 72.6 percent drop from 1986/87.
- revenue from Manitoba customers increased from $508 million in 1987/88 to $569 million in 1988/89.
- a net income loss of $26.4 million was registered.
- reserves dropped from the 1986/87 high of $137.3 million to $92.4 million in 1988/89.

Saskatchewan:

- the proportion of thermal generation and the volume of energy imports increased due to the drought's effects.
- fuel, water and purchased electricity costs increased in 1988 by 28.9 percent from 1987, mostly because of the decline in hydroelectric generation and an increase in total system energy requirements.
- net income before finance charges increased 13.8 percent from 1987.
- operational problems were encountered at two of the thermal power stations. Low water levels, reduced water quality and high temperatures of the cooling reservoir water required reductions in generation capacity.
- hydropower was 37.5 percent below normal in 1988.
- electrical energy was imported to meet demands.
- SaskPower revenues from gas declined 2.6 percent from 1987 to $298 million in 1988. This decline was mainly a result of the warm winter.
- Saskoil's (now know as Wascana Energy Inc.) production of crude oil was apparently not adversely affected and increased 16 percent from 1987 to 1988.

Figure 6. Time series (1960 to 1989) of annual heating and cooling degree-days, Regina and Saskatoon, Saskatchewan (Wilson, 1990)



Alberta's energy implications of the 1988 drought were assessed by Acres International and summarized by Goos (1989). Electricity and natural gas usage was larger in 1988 than in any other year on record. It was expected that natural gas usage, for example, should have decreased because of the relatively warm winter in 1988. However, other factors, such as economic growth, were thought to have masked the sensitivities to climate.

The drought did not seem to cause the extensive adverse impacts for the energy sector in Saskatchewan and Alberta as it did in Manitoba. Manitoba energy production is more sensitive to drought because of its reliance on hydroelectric production.

The indirect effects of climate through its effects on energy consumers are just as important or more important than direct effects. Activities such as irrigation, grain drying, seeding and harvesting are examples of climate dependent agricultural activities that have high energy uses (Hengeveld, 1991). Transportation energy use is also affected by climatic variations. For example winter energy use by cars is lower in mild winters as compared to colder winters.

INSURANCE

Since the local insurance industry is part of a larger global market, the insurance industry on the prairies is sensitive to climate variability within the region and to climate catastrophes all over the world. If natural disasters such as windstorms, hailstorms and drought become more frequent and severe, as is conjectured, more and more policy holders on the prairies would be claiming from their insurance companies. If insurance companies have insufficient surplus funds to service the claims and insufficient insurance coverage of their own, then they would go bankrupt. Smaller insurance companies are at greater risk of this happening. As smaller companies go under, there would be fewer companies paying premiums to the re-insurers who in turn would then be less able to underwrite future risk of climate damage due to smaller reserves. In other words, the industry as a whole would become incapable of supporting more damage.

The 1988 drought is an example where demand for "rain insurance" in the northern Great Plains of the United States rose sharply as agricultural producers realised that it was going to be an unusually dry summer. This situation is also a good example of how insurance companies lost money - Federal Insurance Company lost $20 million and CHUBB Corporation lost $48 million in claims - because claims exceeded the amount that the insurance companies had been underwritten for (Changnon & Changnon, 1990).

RECREATION AND TOURISM

Recreation and tourism can be defined in a variety of ways. The first is to make a distinction between recreation - for the purposes of this paper, the pursuit of outdoor activities by residents of the three prairie provinces or visitors - and tourism. Tourism refers to trips taken that exceed being away from home for longer than one night and that do not have work or commuting as their purpose. It often includes the pursuit of recreation. Tourism can also be categorised by who is doing the traveling. So it becomes possible to talk about domestic and international travel, which refers to people crossing the Canadian border (Wittrock et al., 1992).

Recreation can be broken down according to the season and the type of activity. Thus, Masterton et al. (in More, 1988) refer to winter season (the period between the first and last dates of snow cover of 2.5cm) and summer season (the period starting two weeks after the last date of snow cover) recreation. Outdoor recreational pursuits are then classified by the type of resource base that is required for the activity: dry-terrain-based (e.g., golfing, picnicking, walking, camping); water-based (e.g., sunbathing, swimming, bathing, fishing); and snow- and/or ice-based (e.g. nordic skiing, alpine skiing, snowshoeing, snowmobiling, tobogganing, ice fishing, skating). It is obvious from the above examples that outdoor recreation is extremely dependent on the resource base and on the weather. Weather influences the way people use outdoor recreational facilities as well as their demand for outdoor experiences. It is important to realise, however, that what recreation and how much takes place is not only affected by the weather but also by socio-economic factors such as cultural norms, levels of disposable incomes, school/other holidays, the attractions present and attractions offered elsewhere. An example is the shift in people's preferences from consumptive recreation (e.g. hunting) to appreciative recreation (e.g. hiking) which increases the demand for pristine environments and parks (More, 1988; Arthur and Chorney, 1989; Wittrock et al., 1992).

Tables 11 to 13 show what recreational activities are engaged in on the prairies at present along with the climatic requirements for them.

Table 11. Climatic criteria for outdoor recreational activities (Masterton in Wittrock et al., 1992)

Activity	Temp (^{0}C)	Visibility (km)	Thick Cloud Cover (tenths)	Hourly wind (km/hr)	Snow cover (mm)	Precipitation
Landscape touring	-24 to 32	>4.8	not applicable	<42.8	not applicable	nil
Skiing	-14.4	>0.8	not applicable	<25.7	25.4	nil to light
Snow-mobiling	>-21.1	>0.8	not applicable	<25.7	>25.4	nil to light
Passive Activities	>12.2	>1.6	<8	<33.8	not applicable	nil
Vigorous Activities	12.8 to 31.7	>3.2	<8	<33.8	not applicable	nil
Beaching Activities	>17.8	>1.6	<8	<25.7	not applicable	nil

Table 12. Minimum climate related requirements for summer recreation activities (More, 1988)

	Water Based Activities				
	Motor Boating	**Water Skiing**	**Sailing**	**Fishing**	**Swimming/ Sunbathing**
Air Temperature (^{0}C)	15 to 35	18 to 35	10 to 35	15 to 30	15 to 30
Wind (km/h)	<50	<15	15 to 50	<15	<15
Water Temperature (^{0}C)	2 to 20	10 to 20	10 to 18	<18	15 to 20
Precipitation	nil	nil	nil	nil	nil
Lake size:					
Minimum (ha)	>80	>100	>30 to >100	20 to 80	20 to 40
Maximum (ha)	400	800	800	400	800
Lake depth (m)	1.5 to 2.5	>2.0	1.5 to 2.0	0.5 to 1.0	0.5 to 2.0
Carrying Capacity	1 ha/boat	5 ha/boat	10 ha/boat	--	--
Aquatic Vegetation	Minor emergent	minor submergent	Minor submergent	Minor emergent	Nil

Table 12 Continued

	Dry Terrain Activities		
	Camping	**Picnicking**	**Golf**
Air Temperature (^{0}C)	>10	10 to 25	10 to 30
Wind (km/h)	<10	<20	<20
Precipitation	Nil to light	Nil	Nil

Table 13. Climatic requirements for winter recreation activities (More 1988)

Environmental Condition	Nordic Skiing	Alpine Skiing	Snow Shoeing	Snowmobiling
Snow Season	**November to April**	**November to May**	**November to April**	**November to April**
Snow depth (cm)	20 to 30 minimum 60 optimum	20 to 30 minimum 60 optimum	20 to 30 minimum 60 optimum	30 minimum 60 optimum
Snow Density (g/cm^{3})	<0.6	<0.6	0.2 to 0.6	0.4 to 0.1
Air Temperature (^{0}C)	-2 to -15	5 to -20	10 to -40	10 to -30
Snow making (^{0}C)	-6 to -15	-6 to -15	Not applicable	Not applicable
Wind (km/h)	<20	<15	<45	<45
Wind Chill (watts/m^{2})	700	700	1600	1400

WATER SUPPLY AND DEMAND

In the Prairie provinces the interaction of a variable climate with a variable physiography produces a complex runoff pattern. The average annual runoff can vary from less than 1 cm on the plains to 5 cm on the Shield to over 27 cm in the mountains. The smaller the average annual runoff, the greater is its variability and sensitivity to climate variations. An annual runoff of zero is not uncommon in many drainage basins within the Prairie ecozone.

In many basins, the water resources are fully or nearly fully allocated. With annual evaporation exceeding precipitation on the prairies, water supply is dependent on snowmelt runoff from the prairie and mountain regions to replenish lakes, reservoirs, wetlands and groundwater. Any alteration to the critical balance of this cycle could have a significant impact. Climate change may, for example, affect the timing of runoff and precipitation, the form or amount of precipitation, or the amount of evapotranspiration.

Water supply

In past severe drought years, many water quality and quantity problems were experienced (Wheaton and Arthur, 1989)[1]. The lack of available water in 1988, for example, led to an increase in government assistance programs, and the drought conditions resulted in an increase in the consumptive use of water (Arthur and Chorney, 1989)[2].

The paleoenvironmental record indicates that water supply on the prairies is responsive to climatic fluctuations, particularly in the most arid parts of the region (e.g. Vance et al., 1992, 1993, 1995). Both the quantity and quality of surface waters decline during periods of extended drought, reflecting fluctuations in regional groundwater levels that may have been as much as 4m below present levels during the driest intervals of the last 10 000 years (Lemmen et al., in press).

There are a number of closed basins in the prairies that are replenished by surface runoff but have no outflow. These basins are particularly vulnerable to climate variability; for example, during the late 1980s, the water level of Old Wives Lake in Saskatchewan continually declined

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[1] As cited in Wheaton et al. 1992

so that by 1988 it was completely dry. The lake then recovered following a series of wet years.

Farm dugouts are important rural water supply sources for domestic and agricultural use and are also sensitive to climate variations because they are usually designed on a two year return period. With climate change, the rural population will be particularly affected by changes in water supply (Wheaton et al., 1992).

Water demand

The largest single loss of water in the Canadian prairies is a result of evaporation (e.g. Nicholaichuk, 1991)[2]. High evaporation rates from reservoirs and lakes will reduce the availability of water for other uses. Evaporation rates in the future can be expected to increase further due to the increased temperatures.

The major consumptive use of the remaining water is by the agricultural sector through irrigation. When land is irrigated, as much as 70 percent of water in a channel may be lost through canal seepage and evaporation during the transportation of the water. Water applied to the land is consumed during the evapotranspiration process which occurs in living plants, and through percolation below the root zone. The unused water drains off as return flow to the river system.

AQUATIC ECOSYSTEMS

Although issues surrounding climate variability and change, and global warming in particular, are increasingly the subject of study, the impacts of such change on freshwater systems have received considerably less attention (Carpenter et al., 1992; Vitousek, 1994). This lack of study is particularly apparent within the Prairie Provinces. A major exception to this trend is the work that has been carried out in the Experimental Lakes Area (ELA) of northwestern Ontario. While not part of the Prairie region this work is significant both because of the physical proximity (and hence relevance) of ELA to the Prairie Provinces and because of the more general insights into the possible consequences of climate change.

Hydrologic regime

In the ELA recent changes in climate have dramatically reduced flows in the small streams that feed those lakes. As a consequence, several permanent first-order streams have become ephemeral and chemical exports from the small catchments to the lakes have been reduced. The many studies conducted by Schindler and his coworkers have demonstrated that the relationships among the hydrology of these streams, patterns of chemical export and lake ecology are very complex and in many cases, counterintuitive.

An understanding of climate impacts on the hydrologic cycle is thus a crucial first step in determining the consequences of climate change for aquatic ecosystems. The challenge for researchers is to more explicitly link climate change to the hydrologic cycle and then to link an understanding of the hydrologic cycle to the chemical and biotic structure and function of the ecosystem.

Physico-chemical changes

An increase in average air temperature will increase the annual energy and heat budgets of lakes in the Prairie Provinces, affecting mixing regimes, and increasing water temperature, evaporation rates, and the duration of the ice free season. In the ELA warmer temperatures were linked to clearer waters (partly because of a 50 percent reduction in DOC export from surrounding the catchment) and hence greater UVB penetration, deeper thermoclines and eutrophic zones, higher alkalinities, higher concentrations of base cations and nitrogen, lower concentrations of dissolved organic carbon, silica and phosphorous, increased water retention, and microbial sulfate reduction (Schindler et al., 1996a,b; also see papers by Bayley, Schindler and others in bibliography). As discussed by Schindler et al. (1996a), these changes are both complex and dramatic, were not predicted, were, in many cases, counterintuitive and all were a response to slight/moderate climate change. Furthermore, these impacts have major implications for the biological structure and function of these lakes.

The studies conducted at the ELA serve not only to demonstrate the complexity of climate sensitivity but also serve to demonstrate the inherit complexity of these systems. Even in those systems for which two to three decades of detailed data are available the full impact of warmer, drier weather is very difficult to quantify and virtually impossible to predict.

Primary production

In saline lakes and wetlands phytoplankton community structure and chlorophyll *a* have been shown to be correlated with salinity, possibly because of a salinity-linked shortage of nutrients other than phosphorous (Evans and Prepas, 1996). Changes in planktonic diatom communities are so strongly linked to salinity and nutrient availability that they have been proposed as indicators of climate change in Moon Lake, North Dakota (Laird et al., 1996) and in the Yellowstone and Grand Teton National Parks (Kilham et al., 1996).

Sensitivity to temperature, salinity, general water chemistry, frequency and intensity of floods and droughts is also apparent in the macrophyte community. Climate changes that affect these variables can also be expected to alter the structure of the macrophyte community (Poiani et al., 1996).

WILDLIFE AND BIODIVERSITY

Few studies directly involve effects of climate change on prairie wildlife or biodiversity. However, a number address responses (sensitivity) of species to climate variability, notably drought. Aspects of climate change considered in prairie papers included direct effects of carbon dioxide on vegetation, earlier onset of spring, and drought (assumed to result from increased evaporation and evapotranspiration due to higher summer temperatures, which would offset slightly higher precipitation, as suggested by most climate change scenarios for the prairies).

Effects on vegetation.

The effect of drought on biomass and species richness of grassland plants was measured in Minnesota (Tilman and El Haddi, 1992). Decreases in above ground biomass, diversity and species richness were found, with local extinction of many rare species. Annuals were more likely to be lost from the study plots than were perennials, and their loss was not dependent on pre-drought abundance as was loss of perennial species. Little recovery had occurred even two years after the drought had ended.

Effects on wildlife.

Wetlands are defined as "land that has the water table at, near, or above the land surface, or which is saturated for a long enough period to promote wetland or aquatic processes" (Tarnocai, 1980)[2]. Wetlands are maintained by a high water table or frequent flooding. A large supply of water in excess of losses is required. Climate controls the supply of water to the wetlands through precipitation and runoff, and controls the loss of water from wetlands through evapotranspiration. Climate also affects the hydrological status of the wetlands by influencing factors including vegetation development, frost formation and water infiltration into soils. Climatic variations have both direct and indirect effects on the supply and the losses of water and therefore affect the behaviour of the wetlands as well as the feasibility of preserving them (Woo, 1991)[2]. A strong relationship exists among climate, wetland hydrology, vegetation patterns, and waterfowl habitat. Climate affects the quality of habitat for breeding waterfowl by controlling regional water conditions, including water depth, areal extent, and length of wet/dry cycles (Cowardin et al., 1988)[2]. Climate also affects vegetation patterns, such as the cover ratio (ratio of emergent plant cover to open water) (Poiani and Johnson, 1991)[2].

Although much of the extensive northern wetlands remain undisturbed by humans so far, warming may lead to increased human activity that will add to the natural stress that is likely to affect northern wetlands with climatic warming (Wheaton et al., 1992). In other parts of the prairies, wetlands have undergone considerable alteration in the last several decades, suffering from both human-induced and natural changes. This is especially true of prairie wetlands which have undergone human disturbance (e.g. drainage for agriculture and other uses) and drought-induced drying and disappearance. Over 71 percent of prairie wetlands in Canada have been lost due to human activities (Lands Directorate, 1986)[2]. Surveys conducted by the Canadian Wildlife Service of Environment Canada (Brace and Pepper, 1984)[2] indicate that wetland destruction is greatest in Saskatchewan, at 21 percent, as compared to the other prairie provinces. Agricultural degradation of wetland margins also is occurring. On the average, 78 percent of wetland margin area in Saskatchewan has been degraded, 64 percent in Manitoba and 93 percent in Alberta (Brace and Pepper, 1984)[2]. Saskatchewan Environment and Resource Management (1997) indicates that, while agricultural impacts on wetland basins in Saskatchewan have remained steady since 1981, there has been a steady increase on the wetland margins affected, rising from about 60 percent to about 86 percent.

Wetland destruction (amount and rate) may also be affected indirectly by climatic variations (including short term variability and longer term change). In warmer and drier years, wetland margins and entire wetlands are easier to cultivate and are therefore more suitable for agricultural use. Thus, wetland degradation by agriculture and other activities may be accelerated with increased incidence of warmer and drier years (Wheaton et al., 1992). Wittrock and Wheaton (1989)[2] examined how the 1988 drought and earlier dry years affected waterfowl populations. With the wetlands disappearing because of the dry weather and destruction of their habitat through cultivation, the migratory waterfowl are also being severely affected. Their populations had decreased during the dry 1980s and an apparent increase in diseases occurred, mainly due to overcrowding on the remaining wetlands. This indicates what may happen under a future warmed climate.

A considerable portion of the literature involves response of wetlands and waterfowl to drought. Climate explained more than 60 percent of the variation in number of wet basins throughout the Prairie Pothole Region of Canada and the United States, but Parkland wetlands were more sensitive to temperature than were Grassland wetlands (Larson, 1995). The author noted that this may become important to nesting waterfowl if more birds shift to breed in the Parklands, as grasslands advance farther north. Waterfowl production is related not only to the number but also to the type of prairie wetlands (Diamond and Brace, 1991), usually small seasonal and semipermanent ponds, which are likely to be affected by climate change. In North Dakota, for non-waterfowl species as well, the greatest number of breeding bird species was found on seasonal and semipermanent wetlands (Kantrud and Stewart, 1984). Highest overall bird densities were on semipermanent wetlands.

Long-term changes in wetland size and vegetation under differing environmental conditions (usually drought) were modeled for semipermanent North Dakota wetlands (Poiani and Johnson, 1991, 1993; Poiani et al., 1996). As noted by LaBaugh et al. (1996), the response of wetlands to extremes in precipitation, resulting in shifts in major ion abundance and changing salinity-wetland water level relationships, is not usually considered in the relationship between major ion abundance and species composition. Changes in salinity and surrounding vegetation of wetlands has importance in determining not only foraging success (plants and insect prey of birds and other wildlife species), but also suitability of pond habitat (e.g. lack of cover desirable for foraging shorebird migrants, certain types of cover useful in hiding growing young of waterfowl and other species).

Initiation of breeding in prairie waterfowl is related to May temperatures and spring precipitation (Greenwood et al., 1995). Rates of renesting in waterfowl were particularly sensitive to drought conditions, presumably due to the absence of insect prey (Krapu et al., 1983). There are scattered studies involving other species. Variability in wetland conditions affected site tenacity of breeding shorebirds differently for each species in Saskatchewan (Colwell, 1991). Species richness, diversity, and density of grassland songbirds declined in North Dakota during drought (George et al., 1992). Great variability in response existed among different species. In some, nesting success declined due to nest abandonment, presumably due to a lack of insect prey. Larson (1994) clearly summarizes potential effects of climate change (including increased carbon dioxide, UV-B, and temperature, and decreased precipitation) on birds breeding in the northern Great Plains. She suggested that the probable decreases in plant nutritional value, changes in timing of insect emergence, and decreased number and higher salinity of wetlands would result in fewer birds. However, this effect might be mitigated by possible increases in drought resistance and more efficient water use by plants, the longer growing season, and increased plant biomass.

Few mammal studies were noted. Simulated drought conditions depressed captive vole reproduction (Nelson et al. 1989). As a description of how climate could affect vertebrate species by initiating structural changes in the abiotic, rather than biotic environment, Stokes and Slade (1994) studied the use of cracks in the soil of the Great Plains as refuges of small mammals. Voles used cracks less than deer mice, so might be relatively less protected from predators when conditions are drier.

Declines in amphibian abundance have been noted globally, as well as in western North America (Blaustein and Wake 1990). Suggested local causes include acidification of ponds, introduced predators (fish and bullfrogs), and pesticides. There may be synergistic effects between local factors and long-term low-level exposure to increases in UV radiation and temperature from global warming. Hatching success in some species of salamanders and frogs was significantly higher for those shielded from UV-B than those not shielded (Blaustein et al. 1995, 1996). UV-B radiation is probably most detrimental in species that lay eggs in open shallow water, and have a poor capacity to repair UV-damaged DNA.

The studies of wetlands and waterfowl cited above primarily involved local prairie breeders. Species migrating through the prairies can also be greatly affected by climate. The effects of drought on shorebirds migrating through Kansas was addressed by Castro et al. (1990). With more wetlands drained directly due to agriculture, and irrigation resulting in greatly decreased water in the aquifers of some areas, fewer alternative wetlands for staging shorebirds exist in drought years in the interior of North America. Wittrock and Wheaton (1989), examining the impact of drought on Canadian prairie birds, noted that wetland basins, once dry, are often then cultivated and lost even if water conditions improve in future years. They also noted an apparent increase in avian cholera in waterfowl during drought, presumably the result of concentrating birds in fewer extant wetlands, and lowered resistance to disease due to stress and poor foraging opportunities. Productivity of arctic nesting snow geese declined in prairie drought years, as females obtained less stored nutrients on the prairies for later egg production (Davies and Cooke 1983).

Feedback effects on climate.

Changes in boreal habitat could have major feedback effects on climate in several ways. The presence of trees mask the high reflectance of snow, leading to warmer winter temperatures than if trees were absent (Bonan et al. 1992). Deforestation leads to decreases in temperature, even beyond the deforested area. Changes in species composition, as well as spatial distribution of vegetation, can result in both positive and negative feedbacks on climate (Price and Apps 1995). Other feedback mechanisms on climate from changes in the boreal ecosystem include carbon sequestering and methane emissions (Wheaton and Wittrock 1994). Formation of new ponds and flooding of existing peatlands would result in changes in the carbon pool and methane production, acting as a positive feedback on greenhouse gases (Bridgham et al. 1995). Fire is expected to increase with climate change in the boreal forest. This would result in an increased release of carbon dioxide during the fire, and higher decomposition rates for decades later would continue to release more carbon dioxide (Wein and deGroot 1996). Changes in wildlife abundance can also have a large effect. In a Minnesota study, increases in beaver populations resulted in almost a four-fold increase in methane emission from peat wetlands (Bridgham et al. 1995).

Effects on wildlife or biodiversity.

The effect of drought on birds was studied in subalpine areas of northern Utah (Smith 1982). The number of species decreased most in aspen areas. Densities of singing males decreased, as did numbers of insectivorous birds, and insectivorous hummingbirds disappeared. The number of granivorous finch species increased. The author related this to changes in food resources, and concluded that avian communities in deciduous vegetation may be more affected by drought than those in coniferous vegetation. Numbers of birds in alpine meadows changed very little. On high mountain slopes in western Colorado, the Uncompahgre fritillary butterfly declined in number and went extinct during the hot dry summers of the late 1980s (Mlot 1991).

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CHAPTER 4

IMPACTS OF CLIMATE CHANGE

INTRODUCTION

The previous chapter has identified examples of regional sensitivities to past and current climatic variability and has shown that systems vary in their sensitivity to climate. But how sensitive will these natural ecological systems and socioeconomic systems be to possible future climate change? Clearly, both the magnitude and rate of climate change are important in determining sensitivity of systems. Unfortunately, quantitative projections of the impacts of climate change on any particular system within a geographical region are difficult to determine because regional-scale climate change predictions are uncertain.

AGRICULTURE

Biological systems are very complex. The growth and development of plants and animals and the impacts of climate change do not lend themselves to simple correlations. Biological systems will adapt through natural selection. Breeders will impose upon the natural selection process those characteristics that will optimize yields under changing atmospheric and climatic circumstances (O'Brien, personal communication). As such, it is very difficult to state with certainty the impact of these atmospheric and climatic changes or the outcome of the adaptations, which will be natural and human induced.

Before an assessment of the impacts of climate change on the agricultural sector, or any other sector, can be accomplished with some confidence, information about the diurnal and seasonal changes in the temperature, cloud cover, radiant energy and aspects of precipitation state, frequency, intensity and amount must be obtained. There are currently very significant gaps in the knowledge about future climate, particularly with respect to regional conditions. It is, therefore, impossible to predict the outcomes. With the information at hand, scientists have begun to assess the potential disturbances to the current natural and cultural systems. While this work should be respected for its proactive posture, a healthy scepticism must be maintained (Ted O'Brien, personal communication, July 30, 1997). An appreciation of past climates provides a useful starting point for an understanding of climate change.

The best analogue in the paleoenvironmental record for current model predictions is the period between about 5000 and 7000 years ago, when mean annual air temperature was 1-2^{0}C warmer, and growing season precipitation was 15 percent lower than at present, over much of the prairie region (Vance et al., 1995). At this time, regional water tables lay more than 4m below present levels across much of the agricultural belt, while the few remaining surface water bodies were generally saline to hypersaline. A scarcity of surface could impact many aspects of agriculture, including supplies for irrigation and watering livestock. In addition, past intervals of increased aridity were associated with greater landscape instability. As recently as 200 years ago, areas of presently stabilized sand dunes, which are used extensively for grazing cattle, were fully active (Lemmen et al., in press). Under similar climatic stress, these areas could no longer have agricultural value.

According to Williams et al. (1988) there is potential for a thirteen fold increase in the frequency of drought under climate change. Future droughts also could become more severe than in previous years, such as during the 1930s and in the 1980s, making agriculture even more vulnerable and its capacity to adapt even more difficult. This may be reflected in an increased demand for irrigation, for example.

Most climate change scenarios for the prairies show an increase in temperature and reductions in soil moisture with a doubling of atmospheric carbon dioxide. The predicted increases in temperature would likely lengthen the growing season (where growing season is defined by mean daily temperatures above 5 degrees Celsius) for the prairies. But according to Raddatz and Shaykewich (1997), for the eastern portion of the Canadian Prairies a warm summer reduces evapotranspiration as above normal temperatures hasten crop maturity (defined as the effective growing season of the crop). Where soil moisture supply is limited (the normal condition for non-irrigated prairie crops), crop yields would decrease in concert with this decrease in overall evapotranspiration from the crops. Higher air temperatures would increase evapotranspiration where soil moisture is readily available. Thus, under climate change scenarios, higher temperatures and lower soil moisture may adversely affect dryland agriculture.

Various studies of the climate record have suggested that over many land surfaces world-wide there has been a decreasing diurnal air temperature range since 1950 (IPCC WG I, 1996). This decreasing range has usually been due to the faster rise of night-time temperatures which appears to be the result of increased cloud cover. If this general observation holds in future, then there may be no additional stress at the plant level and a reduced risk of frost.

Also, increased crop production may be possible in northern regions where suitable soils exist. However, while the temperature rise may or may not be beneficial to crop growth, the extra heat would likely increase the potential risk of insect infestation (O.Brien, personal communication). Some species may increase the number of generations occurring in the summer season and some more southern species may move northward.

According to O’Brien (personal communication), the potential impact of higher temperatures on weeds is less clear. Some species thrive in cool, wet conditions while others thrive in warmer conditions and are more adapted to dry conditions. (No species prefers moisture stress). Therefore, the competitive advantage will go to the plant (weed or cultivar) that is most adapted to the prevailing conditions.

As for many of the common diseases, the tendency is for them to be more productive in humid conditions. Many spores propagate more readily in larger canopies with humid conditions and on parts of the plant that are wetter. Therefore, if drier conditions are perceived to be the norm, one might expect a reduced impact from wind borne diseases that do better in humid conditions. Those diseases that are transmitted by insects may be an increased burden to agriculture (O’Brien, personal communication).

Under changed climatic conditions the performance of herbicides will need to be evaluated. For example, under dry conditions farmers may be less likely to apply herbicides, or the cost of herbicide application under a low yield condition is not economical. But this is not a simple issue. There are many herbicides and each has its specific response. Weeds are annuals or perennials. Herbicides act on the metabolism of the plant. If the plant is metabolizing slowly because of moisture stress, then the herbicide may be less effective. In addition, the plant may not absorb the active ingredient as much as during better growing conditions. But at the same time, the weed is stressed by the lack of moisture. If the weed is able to access moisture, then the herbicide is likely to be effective. Competitive advantage goes to the plant that emerges from the ground first or has the deepest roots (O’Brien, personal communication).

Precipitation could be the limiting factor for agriculture production on the prairies based on the current models. Some models have shown an increase in precipitation while others predict a decrease. In addition, not all parts of the prairies will experience the same effects. Precipitation may increase in the eastern prairie and decrease in the west (Brklacich et al., 1994).

Given the potential changes in production variables, Williams et al. (1988) estimates that the average potential yields may fall by 10-30 percent.

Warmer conditions in the summer can lead to stress on livestock due to dry pastures, poor hay and feed production and shortages of water. On the other hand, increased temperatures during the winter months can reduce the cold stress experienced by livestock remaining outside, as well as reduce the energy requirements to heat the facilities of those animals inside. In areas where moisture is not a critical issue, the increased temperature would have a positive effect on the growth of the pasture, and provide better feed for livestock.

FOREST ECOSYSTEMS

The Western Canadian boreal forest is particularly sensitive to direct effects of climatic changes such as drought and indirect effects such as fire and insect disturbances. The boreal forest is the ecosystem that is expected to be affected the most by future climatic changes because of its high latitude location and because of its climatic sensitivities.

Key climatic factors appear to be the rate of change and extremes, especially drought. Drought events are significant through their effects on soil water availability, fire, insects and diseases, and the carbon budget. Estimated impacts of possible future scenarios include:

- growth and productivity could improve in central and northern regions, especially on favourable sites, and decrease in the south, especially with increased droughts.
- climate zones will shift northward, putting stress on the forest ecosystem with rapid changes.
- disturbances such as fire, insects, and diseases could increase, especially with already stressed ecosystems.
- increasing frequency and intensity of drought could result in decline and dieback as well as increasing stress from other disturbances such as fire and insects.
- demand for new tree species for regeneration could increase.
- the region fluctuates between being a net source and a net sink of carbon depending mainly on natural disturbances such as fire and insects, and forest management practices.
- net loss in the total area of the western Canadian boreal forest is expected.
- changes in land-use potential would affect multiple use of forest lands (e.g., biodiversity, increasing agriculture, recreational and other non-timber uses).
- increased productivity could benefit Canadian consumers and result in losses for producers.

A warming of even 1°C could cause the boreal forest to move northward (Horgan 1989, IPCC WG II, 1996). The forest-grassland transition and the predominately forest subregion in western Canada are only separated by about 2°C in mean annual temperature. The effect of a 2°C increase is mainly manifested through increased evaporative demand, reduced soil moisture, and, therefore, more severe drought. This results in reduced stomatal conductance, reduced growth, and more severe dieback events, especially when combined with other stresses (Hogg p. comm. 1997). A persistent increase even that small could result in a pronounced mismatch of climate and ecosystem (Wheaton and Thorpe 1989).

In general, the circumpolar boreal forest is likely to decrease in area, biomass, and carbon stock, with a move toward younger age-classes and considerable disruption at its southern boundary. Carbon dioxide enrichment is estimated to have less effect than in warmer climates.

Rising temperatures tend to stimulate the development and seed germination of many species. This would enable the northward shift of forest cover if not constrained by soil type, for example. A longer growing season would tend to increase growth and productivity, depending on water and nutrient availability and the frequency of fires (IPCC WG II, 1996).

The boreal forest's response to a pole-ward shift of climatic zones is not clear, but the IPCC WG II (1996) has high confidence that the northern tree-lines are likely to advance slowly into regions that are currently tundra. Existing populations of trees near tree lines could have positive growth responses. Vegetation zonation shifts could have considerable socioeconomic and environmental implications, depending on the rapidity of the changes and the affected sectors' awareness and adaptability.

Southern parts of the boreal forest may be replaced by grassland or other vegetation, or by agriculture where soils are suitable. Species shifts may occur in the mid-boreal regions. Large portions of the forest will be mismatched with their climatic zone (IPCC WG II, 1996). For example, much of the current boreal forest in western Canada would have a prairie-like climate (Rizzo and Wiken 1992, Lenihan and Neilson 1995). On the southern edges of the forest, reduced winter chilling may disrupt both vegetative growth and reproductive processes. Unfortunately, it is not yet possible to predict transient forest responses at a regional to local level (IPCC WG II, 1996).

Forests will be forced to migrate to keep up with the shifting climatic zones. Each species has different tolerances, genetic variances, and dispersal rates, so each will differ in its adjustment to the changing environment. Therefore ecosystems will not migrate as a unit in response to shifting climatic zones. The results could be new assemblages and new ecosystems (e.g., Singh and Wheaton 1991). Some species may be able to persist in the current location for some time, until certain survival thresholds are reached or disturbances occur, but others are expected to die out (Morecroft et al., 1997). A rapid rate of climatic change beyond the immediate adaptive range of many boreal tree species will result in increased failures in regeneration and restocking efforts in harvested areas. The global warming will reduce natural regeneration of present commercial tree species, particularly in delicately balanced southern geological transition zones (Singh and Wheaton 1991).

The northward expansion of mature boreal forest would tend to be slower than the loss of southern forest area to grassland and other types. Also, the squeeze into the tundra is limited. The warmer temperatures might improve the climate for the woodland, but may not compensate for the inability of the acid till soils to support a closed-crown forest. The rate of migration may not be rapid enough to keep pace with the climate and the soils may be an infertile barrier to the forest's northward movement. The summer drought with more frequent fires and insect invasions and shifting permafrost could change the subarctic black spruce woodland into predominantly jack pine. So the grasslands may squeeze the boreal forest from the south and the northward barriers may decrease the total area of the forest (Rowe and Rizzo 1990).

The climatic control of the southern limit of the boreal forest indicates that even a slight shift toward drier climatic conditions could have a significant impact on natural conifer distribution over the long term. Large areas of the boreal forest appear to be sensitive to climatic change, especially where the annual precipitation minus potential evapotranspiration is less than 15 cm. "If global change leads to substantially drier conditions, then there could still be eventual losses of forest cover from these low-elevation areas, possibly leading to fragmentation of the western Canadian boreal forest." (Hogg 1994:1843).

Fire frequency is expected to increase with increasing drought frequency because drought and fire are closely related in this region (e.g., Wittrock and Wheaton 1996). Therefore, if fires are not adequately controlled, they could be a mechanism of accelerating the northward shift of the boreal forest.

The increased carbon dioxide concentrations may act to offset the effects of drought. The direct effects of increasing carbon dioxide increase photosynthesis, growth and water use efficiency in many plant species (e.g., Lemon 1983).

Future climatic warming will change many aspects that influence the fire hazard. These include frequency and intensity of the hazard over time and space, quantity of available fuel, species composition, as well as fire season length, droughts, and lightning. The boreal forest ecosystem is fire dependent, but more rapid increase in fire activity will stress the balances.

Insects are a dominating disturbance factor and during outbreaks they can cause tree mortality over vast areas of forest. If the predicted climate changes take effect, the damage patterns caused by insects may be drastically altered, especially for the many insects whose occurrence in time and space is severely limited by climatic factors (Fleming and Volney 1995).

Impacts on the forest ecosystem of a changing climate are not expected to be smooth and gradual. Changes may be subtle for some time, until ecological thresholds are reached, feedbacks intensify, or until disturbances occur. Neither will changes be easy to predict in most cases. Complex interactions, feedbacks, and nonlinear relationships will cause surprising results.

The future of the boreal forest appears quite uncertain in the face of climatic change. The forest may be increasingly shaped by climatic induced growth, disturbance, decline and mortality. Forest management may become a more critical factor.

Recent results from climatic impact work regarding disturbances are summarised in Table 14.

ENERGY

An increase in mean annual temperature of several degrees Celsius would result in a longer frost free period, more evaporation in the summer and fewer or shorter cold spells in the winter. Changing precipitation patterns would also be likely to occur but these are less predictable. In addition to changes on the plains, all three provinces would be impacted by changing temperature and precipitation patterns in the mountains - the source of water for the major prairie rivers. These changes will have a number of direct and indirect impacts on energy production, distribution and use. Some of the major implications are:

- Higher mean temperatures will create a reduced winter heating load and the potential for increased summer cooling load.
- Surface waters are likely to be warmer and the increased evaporation result in reduced volumes and water quality.
- There is likely to be an increased demand for water to meet domestic, industrial and agricultural requirements.
- Changes to soil water availability could result in changing land use, particularly in marginal areas, and the demographic changes that would be required to accommodate changed land use.

A significant potential impact on hydropower production for all three provinces would occur through the effect of droughts and increasing temperatures on river flow. Glaciers are an important water source that have undergone significant change. A general deglaciation trend has occurred in the Northern Hemisphere since the 1570 AD to 1730 AD period of cool summer temperatures ("Little Ice Age"). Canada's extensive glacier resources are no exception. Glaciers in the eastern Rocky Mountains have lost between 25 and 75 percent of their Little Ice Age maximum volume over the last century. This trend will augment stream base flow in the shorter term (20 to 30 years). In the longer term (30 to 100 years) the reduced melt volumes from glaciers will reduce river flow, particularly in summer, from these sources (Demuth 1996).

Loss of base stream flow is especially important during dry summers. Decreased base flow contribution and changes in timing would influence hydro-power reservoir operating strategies in preparation for periods of peak winter consumption, for example. Such effects would tend to diminish with distance from the eastern slopes (Demuth 1996, Demuth p. comm. 1997).

Possible reduced hydropower production caused by decreasing water flow in a changing climate could be compensated for by increasing thermal power production resulting in an increase in fossil fuel consumption and greenhouse gas emissions (Wittrock and Wheaton, 1992).

Climate and energy have many complex direct and indirect interactions. The following summarizes the expected effects of climatic change on Manitoba Hydro:

- diminished river flow and its effect on hydraulic generation is thought to be the most significant. It could make the current planning criteria for new plant and operating practices inadequate.
- multiple freeze-ups and break-ups would reduce winter hydraulic capacity.
- transmission line icing would decrease performance of transmission facilities.
- decaying permafrost would destabilize towers and other structures.
- increased air temperatures would increase conductor resistance and result in increased energy losses.
- increased winter temperatures would adversely affect the construction and use of winter roads in remote areas, thereby reducing winter shipping and maintenance.

Table 14. Forest changes possible with future climatic change in the western Canadian boreal forest - some results from other studies [Refer to Table 1 (Wheaton et al., 1992) for studies previous to about 1991].

Characteris-tics	Impacts	Climate Scenarios	Impact Model	Uncertainties/ recommendations-examples	Source	Comments

Characteris-tics	Impacts	Climate Scenarios	Impact Model	Uncertainties/ recommendations-examples	Source	Comments
Growth, productivity, competition, regeneration	Biomass change of more than –50%, +10%, +30% and +40%	GFDL, UKMO, GISS, and OSU	FORSKA2	Effects of climatic variability, including droughts. Climate-response relationships.	Price and Apps 1996	Results varied significantly with different climatic scenarios.
	Reduced productivity and increased mortality in a large part of the south.	CCC GCMII90 (4-5°C increase in mean temperature and 11% increase in precipitation).	Moisture index	As above. Disturbances are likely to exacerbate the impacts.	Hogg and Hurdle 1995	
	Biomass increases in general. Seasonal changes are summer decreases and spring and fall increases.	CCC GCMII (1990)	Climatic index of biomass potential	Other climatic scenarios should be used.	Wheaton and Wittrock 1993	
	Conifer dieback and replacement by grasses.	GISS 1988 and GFDL 1987	Canadian Climate Vegetation Model (CCVM)		Lenihan and Neilson 1995	Changes are drought induced.
Zonation and area	Aspen parkland climate would replace much of the south and west portions.	CCC GCMII 1990	Climatic moisture index	As above.	Hogg and Hurdle 1995	
	No pronounced northward shift of vegetation zones. Species invasion of types not currently found are indicated.	GFDL, UKMO, GISS and OSU	FORSKA2	See above at Price and Apps 1996.	Price and Apps 1996	
	Northward shift of boreal and grass prairie formations, especially with GFDL.	GISS 1988 and GFDL 1987	Canadian Climate Vegetation Model (CCVM)	Transient response of vegetation.	Lenihan and Neilson 1995	

- decreased winter heating loads and increased summer air conditioning loads. The net effect should be a reduction in annual peak load.
- the cost of energy supply for long-term firm export contracts was forecast to increase with climatic warming.

Indirect effects include:

- mitigation policies could result in restrictions on fossil fuel consumption, resulting in an increased demand for other energy sources such as hydroelectricity (which, in turn, may be difficult to satisfy if streamflow decreases).
- changes in social, agricultural and industrial activities could affect Manitoba Hydro's business.
- climatic change impacts may be more adverse in surrounding jurisdictions; in this instance, Manitoba may enjoy a competitive advantage.

An assessment of possible impacts on the energy sector in Alberta was undertaken by Acres International Limited (Goos 1989). The findings were based on the use of the Goddard Institute for Space Studies results for a 2xCO_2 climate simulation:

- net saving of about 0.5 percent of total electrical consumption resulting from the balance of the decrease in winter months and increase in summer months. Heating degree-days were projected to decrease by 20 percent.
- natural gas consumption would also flatten out, decreasing in winter. About 80 percent of the use is for heating and this amount would decrease by about 20 percent.
- overall system efficiency would increase (investment saving of over $300 million).
- marked shift in electrical energy requirements within specific sectors. For example, irrigation energy demands could increase by 20 percent.

Oil production over much of the Prairies will rely increasingly on the availability of water, either for waterflooding or for the production of steam for thermal recovery of heavy oil and bitumen. Water can be pumped into the reservoir as a liquid to assist in pressure maintenance and to help push more oil to the producing well. In heavy oil and bitumen deposits steam is forced into the reservoir to make it move more freely. Where these procedures rely on the availability of near surface ground water or surface water, there is the potential for oilfield use to compete with other uses.

Electricity has the potential to be most severely impacted if climate change becomes a reality. Thermal power stations become less efficient as surface water temperatures increase and, potentially, volumes decrease. Hydroelectric production will have to compete with a number of other uses, primarily agricultural, for the diminishing water supply. Increased demand for water pumping and summer cooling and a decreased winter demand could push electrical utilities into a summer peak load position.

Renewable energy is not immune to climate change on the Prairies, although the impacts are far less clear. Changing temperatures, season length and moisture regimes could result in the production of different crops in the agricultural sector; this may or may not have an effect on the potential of agricultural biomass for renewable energy production. Similarly, the longer term impacts on the forestry sector are not well understood. Increased environmental stress, particularly at the southern margins of the boreal forest, would have a negative impact on the availability and productivity of biomass, at least from the southern areas. Year round availability of solar energy might be affected by seasonal changes to precipitation or increased cloud cover if evaporation increases globally. Wind regimes will likely change; whether the effects would be positive or negative remain to be determined.

Table 15 summarizes the possible impacts of climate change on the energy sector within the Prairies.

Table 15. Summary of possible climatic impacts on energy sectors.

Sector	Climatic Change	Impacts	Reference[a]	Confidence in Sensitivity	Comments/ Region
Energy Demand	Increased temperature	Increased air conditioning and decreased heating; decreased winter transportation fuel and block heater demands	Various, e.g. Hengeveld 1991, Raban 1991	High	
	Decreased wind	Heating effects	IPCC WGII 1996		
	Humidity and cloud changes	Space conditioning effects	IPCC WGII 1996		
Energy Conversion	Increased temperature	Slightly less efficient thermal efficiency	IPCC WGII 1996	High	
	Changes in water availability	Cooling water quantity and quality	after IPCC WGII 1996		Supply constraints may be offset by spring runoff and severe summer storms depending on storage availability
Energy Transport and Transmission	Increased temperature	Pipelines and other infrastructure over permafrost are vulnerable; lower capacity of power lines	IPCC WGII 1996	High	
	Increased freezing rain	Power line icing	IPCC WGII 1996		
	Increased frequency and severity of storms	Effects on power lines- interrupted energy transmission	IPCC WGII 1996		
Coal Industry	Long term decrease in glacier runoff, decrease in summer soil moisture Decreased or changed river flow	Decreased hydropower production Increased demands for thermal production Increased demand and use for coal	Demuth 1996, Wheaton et al. 1992 (Drought analogue)		

Table 15. Continued

Sector	Climatic Change	Impacts	Reference[a]	Confidence in Sensitivity	Comments/ Region
Renewables- Hydroelectricity	Increased temperature Glacier retreat will increase streamflow initially, with long-term decreases	Changes in production capacity; changes in timing of water supply, with less dependable timing.	IPCC WGII 1996, Demuth 1996, Wittrock 1992	Medium	
Solar Energy	Changes in cloud cover and storms	Changes in production capacity	IPCC WGII 1996	Low	Wind and solar energy systems would be especially vulnerable to changes in extreme events (IPCC WGII 1996)
Wind Energy	Changes in storms, wind regime, e.g. speeds, direction, and timing.	Operational hazards	IPCC WGII 1996	Medium	
Biomass Energy	Reduced soil moisture and increased season length Increased frequency and severity of severe storms	Reduced and/or increased variability of biomass supply; change in crop types	IPCC WGII 1996	Medium	
Energy Extraction	Increased temperature-increased permafrost melting Reduced soil moisture, longer seasons	Infrastructure problems with melting permafrost	IPCC WGII 1996	High	
Pollution Control	Increased temperature	Increased surface level 0_3 formation and increased control needs	IPCC WGII 1996	Medium	

[a] with additions by the authors

INSURANCE

The insurance industry on the prairies will not only be affected by climate change within the region but also by climate catastrophes all over the world which will result in changes to their reinsurance rates and availability. With a greater frequency of climate related disasters on the prairies such as crop failure due to drought, pests or storms, demand for insurance will increase. Despite rising demand for insurance which would result from an expectation on the part of individuals that climate change will lead to greater losses to property and crops, smaller insurance companies and policy holders may be unable to afford the higher premiums which will accompany the higher risk. Underwriters may also be less willing to accept this risk. Crop insurance in the Canadian prairies is administered and supported by the three provincial governments. As such, producer premiums may increase, or taxpayers will be expected to carry the increased expenditure on crop insurance.

The economy is affected at a more local level too. If the insurance industry decides to solve its risk problem and vulnerability to climate change by refusing coverage then disaster victims will have to be carried by the tax payer or individuals will have to pay the price themselves. In many cases this could mean the loss of everything. The unavailability of insurance coverage also makes it difficult for an economy to recover after a disaster as witnessed by the situation in Florida following Hurricane Hugo. Insurance coverage was withdrawn and lenders were unwilling to make the loans necessary for reconstruction without the availability of insurance. Even if insurance is available but the premiums have become exorbitant, then many new and existing business ventures will no longer be feasible because of high costs (IPCC Working Group II, 1996; Knox, 1996; Nutter, 1996; Deering, 1994; Flavin, 1994; Swiss Re, 1994).

Another aspect of insurance that could be affected by climate change is health and personal liability insurance. Direct health effects of global warming are anticipated to be increased mortality and illness due to expected increases in temperatures and duration of heat waves (Wheaton and Wittrock, 1992) and fewer cold-related deaths. Indirect health effects would be aggravated respiratory and allergic disorders spurred on by dust storms, the presence of air pollutants, pollens and moulds. Cancers (such as skin cancer) associated with ozone depletion and indirectly related to climate change are also expected to increase in incidence (IPCC Working Group II, 1996; UNEP III, 1996). Health insurance will cost Canadians more in the future, either as tax payers or as individuals. This will be partly due to increased incidence of skin cancer but also due to other non-climatic factors.

The whole economy can be expected to suffer as a consequence of the effects of climate change on the insurance industry. Insurance companies invest their funds in the financial sector. If funds in the insurance industry decline due to bankruptcy or having to pay out large amounts of money in claims, less will be invested in the local and global financial markets.

RECREATION AND TOURISM

Many of the surface waterbodies in the prairies tend to be shallow and eutrophic. Warmer temperatures will encourage algae and plant growth. Since increased algae and plant growth utilize large amounts of oxygen, this may lead to fish kills due to a reduction in dissolved oxygen. The result may be reduced recreational fishing at many locations. The increased algae and plant growth will also reduce the quality of other water based activities such as swimming and water skiing.

Increases in air temperature will likely result in a longer season in which water based and dry terrain activities can take place. However, decreased lake area and depth due to rising temperatures could result in less opportunity for sailing, boating and water skiing. Decreased runoff volumes and shorter runoff periods in the spring and early summer will also influence the quality of white-water rafting and kayaking. While the summer season may be extended and provide more opportunities for outdoor recreational activity, the bulk of recreational activity may continue to take place at the same peak times as it does now: around the school holidays (More, 1988; Arthur and Chorney, 1989; Wittrock et al., 1992).

Golfing, picnicking and camping opportunities will all increase because of the warmer and longer summers. Irrigation and the costs thereof can be expected to increase for golf courses, camping and picnic grounds maintenance as a result high potential evapotranspiration rates.

Changes in wildlife habitats and the decreased severity of winters will result in alterations of the distribution and numbers of big game, waterfowl, and upland game bird species. As the prairie ecozone displaces the boreal forest, species that are adapted to the prairies and aspen parkland can be expected to increase in these areas. Milder winters also may mean higher winter survival rates of species not adapted to cold and snow. The drying up of potholes that is expected to accompany rising temperatures will in all likelihood also lead to the reduced production of waterfowl. Lower lake levels could also lead to the exposure of nesting sites to predators (More, 1988; Wittrock et al., 1992). Many of the prairie species will move north. Wildlife enthusiasts and bird watchers can look forward to more sightings of winter survivors and they may travel north in order to view wildlife which they now view in the south. Hunting activities can be expected to shift north along with the wildlife population. This may have implications for out of province hunters who will have to travel longer distances in order to hunt. They may be unwilling to do so, especially if the costs become prohibitive. The species hunted are also likely to change as hunters adjust to new species in their habitual hunting grounds.

An extended summer season does not bode well for activities such as skating, ice fishing, snowmobiling, cross-country and downhill skiing. The indirect effects of this include the loss of tourism revenues to local restaurants, hotels and other forms of amusement as well as the loss of jobs for people within the community.

Very little analysis has been done on how, and the degree to which, economies will be affected by the impacts of climate change on recreation and tourism. Speculation is that for those activities requiring little in capital development or operating expenses, the economic impact of shifting recreation patterns will be negligible. Activities involving facilities that are costly to construct and maintain are expected to incur the greatest economic repercussions. Downhill skiing is an example of such activities.

WATER SUPPLY AND DEMAND

The literature exploring the effects of climatic change on water quantity is extremely limited for the Canadian Prairies (Wheaton et al., 1992). Schwarz and Dillard (1989)[2] examined the Saskatchewan River basin which covers much of the prairie ecozone and includes major population centres in Alberta and Saskatchewan. Its water resources are dependent on the snowfall and snowmelt regime in the mountains. There is no consensus on projected changes in runoff from the Rocky Mountains (Environment Canada, 1994) but if the annual snowpack in the mountains is reduced, there will be a significant impact on the supply of water that flows through the basin The timing of this snowmelt is also critical. If the melt is early and rapid, producing a runoff that exceeds the storage capacity of the reservoirs on the rivers, water will have to be released. This could lead to a shortage of water later in the year (Schwarz and Dillard, 1989)[2].

Climate change and hydrology

It is first necessary to understand how climate may be modified over the region before we can assess the impacts of climate change on water supply and demand. Several studies have attempted this for Canada and most base their analysis on a climate projection generated by a computer-based general circulation model (GCM) of the climate system (Environment Canada, 1994).

From Wheaton et al. (1992), the following, sometimes conflicting, interpretations of model results give an indication of the possible impacts on the hydology:

- Cohen et al. (1989) draw some conclusions about the effects the changes implied by these scenarios will have on the agricultural sector. A GISS84-type climate with an increase in the water demand in the agriculture sector would not have much effect on the other water users. The situation would be similar with the OSU scenario. In contrast, the GFDL scenarios would have serious implications for the whole range of water users. There would have to be a major policy response to the water shortage.

- The decrease of runoff shown by the GFDL scenario results (e.g. Cohen et al., 1989, Cohen, 1991, Thomas, 1990) would have serious implications for the amount of water available. On the other hand, the increase in runoff shown by the GISS results would allow for potential increases in water supply (Bjonback, 1990).
- Thomas (1990) remarked that although GCM results project a decrease in the magnitude of the snowpack and an early disappearance of the snowpack, clear agreement is lacking about the hydrological consequences of these

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[2] As cited in Wheaton et al. 1992

effects. Thomas suggests that the use of surface models that vary in complexity makes it difficult to make direct comparisons of the results.

- Some of the GCM scenarios for an equivalent doubling of CO_2, indicate an increase in the amount of average annual precipitation, a larger number of extremes in weather and greater frequency of severe storms, e.g. thunder storms. Such consequences could, in turn, cause problems in storm drainage systems, and runoff extremes could affect flood control measures and speed up the deterioration of dams and flood control structures (Schwarz and Dillard, 1989).

- The climate change scenarios show increased annual precipitation. What they do not show is the change in intensity and the timing of the extreme precipitation events. According to Jacobs and Riebsame (1989), and Riebsame (1989), more intense precipitation events over durations measured in hours or days would cause more variability at time-scales that are of interest to flood managers. Extreme precipitation events for periods of months or years would give rise to variability that would be of greatest interest to water supply planners. More research is needed regarding possible changes in intensity of rainfall events and changes in precipitation variability.

- The climate has been characterized by extreme weather events in the past, such as floods and droughts which can have serious implications for sectors such as agriculture, energy and human health. This has led to the construction of many structures (e.g. dams, weirs etc.) to minimize the impacts of these extreme events. Yet these structures were designed on the basis of the magnitudes and flood frequencies of past events, not for what may happen with future global warming. The magnitude and frequency of extreme events could increase with global warming (Jacobs and Riebsame, 1989; Lins et al., 1990). The timing and amount of spring runoff could also change with global warming (Nemec, 1989).

- Nicholaichuk (1991) states that there will be changes in stream flows and flood risks. He also cites results of Haas and Marta (1988), who used the GISS84 and GFDL87 GCM results for $2xCO_2$, to estimate runoff. Their results, which indicate an increase in the number of flood events, found the probability of droughts would not be affected. Unfortunately, the term drought was not defined in Nicholaichuk's article and there are several different definitions for the term drought. The definitions depend on what type of drought is being considered (e.g. hydrologic drought versus agricultural drought).

Depending on the model selected, the predicted prairie runoff could vary from below normal to above normal. While GCMs agree on large-scale changes to the climate system, GCMs have so far provided little insight into the variability of future climates and regional projections must be treated with caution (Environment Canada, 1994) There are indications that in general, for example,

- summer hot spells in the Prairies could become more frequent, while extreme cold spells in winter would become less frequent
- precipitation patterns will change
- evaporation will increase

There is also uncertainty regarding timing and intensity of extreme events, such as floods and droughts (Wheaton et al., 1992) In addition, temperature increases may not be linear - major or sudden surprises are distinct possibilities (Environment Canada, 1994) All attempts to construct scenarios of the possible impact of climate change are affected by these and other uncertainties. The model scenarios must therefore be recognized as the best assessment possible on the basis of existing scientific knowledge. (Environment Canada, 1994).

Water supply

The inability of the current suite of GCMs to reliably predict climate parameters on a regional scale makes it very difficult to predict the impact on the water supply with any confidence. Cohen et al. (1992)[2] state that it may be appropriate to consider two main types of future situations for the Canadian prairies:

1. "Dust Bowl" scenarios in which reduced snow cover in the Rocky Mountains

reduces water supply in the main stream channels and soil moisture is reduced in the semiarid zone. This scenario would result in more frequent and intense hydrological, agricultural and other types of droughts; and

2. "Opposing Stresses" scenario in which increased snow cover in the Rocky Mountains is combined with reduced soil moisture in the prairie region. This would mean that the prairie region would have to meet new demands for increased protection from spring floods, while providing increased water supply services to downstream areas due to increases in drought frequency and intensity.

Wheaton et al. (1992) provided a list of possible impacts of climate change for Saskatchewan and its water resources (Table 16).

Table 16. Possible impacts of climate change on the water resources of Saskatchewan (Wheaton et al., 1992).

	Possible impacts of climate change	**Confidence**
Saskatchewan River(north & south)	System Reduction in mean annual flow by nearly 20%	Low (GISS84)
Spring Runoff	Increase in volume and spring runoff due to increase in fall and spring precipitation	Low -Medium
Summer Flows	Reduction in summer flow and increased duration of low flow	Medium
Evaporation	Warm temperatures may cause increase in rate of evaporation. However the effect of this may be offset by an increase in precipitation.	Low
Flooding	Increased fall precipitation combined with warmer, wetter springs may result in increase in frequency and magnitude of flooding.	Medium
Drought	Increase in summer temperature and earlier spring runoff may result in increased duration of low summer flows and occurrence of drought conditions.	Medium
Recreational Uses	Impact not known (effect of increased evaporation may be offset by increase in spring runoff).	Low
Ground Water	Impact not known	Low
Water Levels	May increase annual variation in water levels	Low
Hydropower Production	Impact largely dependent on effect of climate change on mountain runoff.	Low
Cooling Reservoirs for Thermal Power Plants	Possible increase in evaporation may be offset by increase in spring runoff.	Low
Erosion	Possible increase in frequency and magnitude of spring floods may increase rate of erosion and deposition.	Medium

Water demand

Water is required by several sectors of society - domestic, agriculture, industry, energy and recreation - as well as by wildlife. Under a warmed climate with possibilities of less available water, each sector of society will be demanding action by the planners to ensure an ample supply of good quality water (Wheaton et al., 1992). As well, there will be increased demand for water in summer for such things as watering lawns and providing for the longer length of outdoor swimming season, for dust control (street cleaning), and for other aesthetic and public uses. More water will also be required to fight forest and brush fires (Pentland, 1984)[2] .

A major source of irrigation water for agriculture is the Saskatchewan River basin. It has been projected that the irrigation network within the Saskatchewan basin will expand. It is believed that by the year 2000 more than 500,000 hectares of irrigated land will be supplied by water from the Saskatchewan River basin (Cohen et al., 1992)[2]. Increases in irrigation would be dependent on constraints which include the availability of water, benefits of added production and impact on the environment.

Because of the warmer weather there will be a greater need for good quality drinking water for livestock, wildlife and humans. Water quality will deteriorate as the quantity of water decreases because the concentration of pollutants, sediment load and salinity will increase. Climate change impacts on wind and water erosion and chemical applications in agriculture will also influence the quality of water. The quality and quantity of urban and rural water supplies may have some impacts on people's health. Rural populations may have more problems because of the greater use of untreated water from wells and dugouts (Wheaton et al., 1992).

If climatic warming reduces the supply of good quality water, more intense conflicts may occur among users for the limited resource. They may arise between urban and rural or industrial and agricultural users, for example. Legislation will be needed to deal with such anticipated problems in advance (Diaz et al., 1984)[2] As well, the demand for interbasin transfers will change with global warming.

For transboundary (international, interprovincial and provincial-territorial) river systems there are formal agreements with respect to how much water must move on to the next jurisdiction. These agreements were tested during the drought years of the 1980s. With future climatic change and with perhaps even less water to go around, these agreements will be further tested. Bjonback (1990)[2] predicts that if the level of water use continues at its present rate, there will be problems in maintaining the required flow for supporting fisheries and ecological uses.

With climate warming all demands on the limited water resource on the prairies will increase. There may also be changes in the type of demand. For example, a warmer climate may make it feasible to change from dryland farming of cereal grains to higher value irrigated crops. Until the climate models are better able to predict changes on a regional basis we must surmise the impact on the demand.

AQUATIC ECOSYSTEMS

Alteration of the hydrologic cycle is one of the most obvious and immediate ways in which climate change will affect aquatic ecosystems (Lewis 1989; Chang et al., 1992). More frequent extreme precipitation events would increase erosion and sediment transport. This would widen stream channels, destroy riparian habitat, and alter aquatic habitat both at erosional sites and at downstream depositional sites. Changes of this type may destroy critical habitat, restrict access to spawning tributaries, and may affect general water quality.

Changes in the timing and extent of runoff may affect both the rate of nutrient inflow and the total loading of nutrients to streams, rivers and eventually to lakes (Carpenter et al., 1992). In streams, any runoff changes in nutrient loadings are likely to affect primary productivity. This is particularly true in the headwater reaches of many of the major prairie rivers where primary productivity is largely nutrient limited (Chambers, 1996).

Demuth (1994, 1995) has shown that changes in precipitation and evaporation patterns may result in a retreat of glaciers along the eastern slopes of the Continental Divide. Runoff from these glaciers is important to the maintenance of flow and habitat in the headwaters of several major prairie rivers. Contributions from glacial melt are particularly important in the transition from summer peak flows to base flow in these systems. Flow reductions resulting from decreases in glacier contribution may be further exacerbated by a downstream increase in water withdrawal for irrigation purposes.

Few studies have examined the effect of climatic variability, especially global warming, on wetlands. Climate change could alter many of the hydrological and other wetland characteristics. The prairie wetlands appear sensitive to changes in snow melt and evapotranspiration, and these should be addressed in impact assessment. Less snow melt and more evapotranspiration would tend to decrease water level amounts in prairie sloughs. Scenarios for $2xCO_2$ indicate shorter snow seasons but greater precipitation amounts. The likely resulting effects on snow cover and snow melt amounts and wetlands are unknown (Wheaton et al., 1992).

Changes in evapotranspiration also will have important consequences for the chemistry and biology of prairie wetlands (Larson 1995; LaBaugh et al., 1996; Poiani et al.,1996) and closed-basin saline lakes which are common throughout the semiarid region (Evans and Prepas 1996). Brine conductivity and major ions are sensitive to changes in precipitation/evaporation ratios (Rawson and Moore 1944; Robarts et al., 1992; Laird et al., 1996; Evans and Prepas, 1996). Changes in conductivity also affect the structure of the phytoplankton community.

The chemistry of wetlands can be dramatically affected by extreme precipitation events and the consequences can extend well beyond the extreme events themselves. Chemical changes include increased salinity during drought, and shifts in anion balance following inundation of vegetation zones (LaBaugh et al., 1996).

In saline lakes and wetlands phytoplankton community structure and chlorophyll *a* have been shown to be correlated with salinity, possibly because of a salinity-linked shortage of nutrients other than phosphorous (Evans and Prepas, 1996).

Sensitivity to temperature, salinity, general water chemistry, and frequency and intensity of floods and droughts is also apparent in the macrophyte community. Climate changes that affect these variables also can be expected to alter the structure of the macrophyte community (Poiani et al., 1996).

Though not strictly a climate change issue, increases in UV-B radiation resulting from loss of stratospheric ozone has major implications for primary productivity in aquatic ecosystems. Some research suggests that the inhibition of primary productivity by UV-B will result in decreased rates of carbon fixation, elevated levels of atmospheric CO_2 and an acceleration of global warming.

The zooplankton community can have considerable impacts on phytoplankton communities on which they feed as well as on the higher trophic levels (e.g. fish) which rely on zooplankton as a major food source. Moore et al. (1996) have argued that climate warming will have major consequences for zooplankton communities since observed climate changes have already caused mid-summer water temperatures in many mid-latitude lakes to approach the thermal tolerance of a variety of zooplankton taxa. Higher summer water temperatures also result in smaller individuals, probably as a result of increased filtering and respiration rates coupled with a decrease in assimilation efficiency. In addition, climate change has reduced the availability of cold water, oxygenated refugia that are important to zooplankton survival during the summer months.

Certain benthic macroinvertebrates (Bothwell et al., 1993,1994) and amphibians (Blaustein et al., 1994, 1995, 1996) are known to be sensitive to UV-B radiation. Climate-induced changes in temperature and dissolved oxygen will undoubtedly affect developmental rates and survival in most aquatic invertebrates and macroinvertebrates.

Many species of fish, such as lake trout have fairly narrow temperature and dissolved oxygen requirements. This species and other cold stenotherms may be threatened by the loss of summer refugia (Schindler et al., 1996). All else being equal, increasing temperatures will allow some freshwater fish species to extend their range into higher latitudes and may cause them to disappear from what is now the southern extent of their range.

The actual impacts of climate change on fish will however involve much more than thermal tolerance. Indeed, the fish community can be viewed as an integrator of many of the impacts discussed above. Changes in the hydrologic cycle are likely to affect the availability and quality of critical fish habitat. Climate-induced changes in the physico-chemical nature of prairie aquatic ecosystems may affect fish directly or indirectly, through impacts on their prey populations.

WILDLIFE AND BIODIVERSITY

Climate change can affect wildlife and biodiversity in many ways (McAllister and Dalton, 1992). Effects may be direct, whether immediate or delayed (e.g. lethal temperatures vs. heat stress), or indirect. Indirect effects include changes in food abundance or availability, habitat loss or degradation, and changes in predation rates, competitive interactions, parasites and disease. 'Cascade' effects may result in massive changes to the ecosystem if keystone species are affected. Dispersal may be a limiting factor, either in innate ability to disperse, lack of source populations, or landscape barriers to dispersal. Particularly for migrants, changes in timing of food abundance at staging versus breeding areas could be very important to survival (Dolman and Sutherland, 1994).

Climate affects the variation in number of wet basins throughout the Prairie Pothole Region of Canada and the United States, but Parkland wetlands are more sensitive to temperature than Grassland wetlands (Larson, 1995). This may become important to nesting waterfowl if more birds shift to breed in the Parklands, as grasslands advance farther north. Waterfowl production is related not only to the number but also to the type of prairie wetlands (Diamond and Brace, 1991).

Larson (1994) clearly summarizes potential effects of climate change (including increased carbon dioxide, UV-B, and temperature, and decreased precipitation) on birds breeding in the northern Great Plains. She suggested that the probable decreases in plant nutritional value, changes in timing of insect emergence, decreased number and higher salinity of wetlands would result in fewer birds. However, this effect might be mitigated by possible increases in drought resistance and more efficient water use by plants, the longer growing season, and increased plant biomass.

Species migrating through the prairies can also be greatly affected by climate change. With more wetlands drained directly due to agriculture, and irrigation resulting in greatly decreased water in the aquifers of some areas, fewer alternative wetlands for staging shorebirds exist in drought years in the interior of North America. Wittrock and Wheaton (1989), examining the impact of drought on Canadian prairie birds, noted that wetland basins, once dry, are often then cultivated and lost even if water conditions improve in future years. They also noted an apparent increase in avian cholera in waterfowl during drought, presumably the result of concentrating birds in fewer extant wetlands, and lowered resistance to disease due to stress and poor foraging opportunities. Productivity of arctic nesting snow geese declined in prairie drought years, as females obtained less stored nutrients on the prairies for later egg production (Davies and Cooke, 1983).

Global warming will not be uniform across regions. If some areas warm more or faster than others, this indirectly may have severe effects on migrants between those areas. Arctic shorebirds are long-distance migrants, dependent on food resources elsewhere at specific times of the year. If the timing of food flushes elsewhere changes more slowly than invertebrate regimes in the arctic, the birds may not be able to migrate early enough to hatch eggs before peak insect hatch (Lester and Myers, 1991). Foraging habitat at staging areas also may be affected by climate change. For example, coastal staging areas used by shorebird migrants may be flooded by increases in sea level, making these sites unavailable to the birds.

Changes in boreal habitat could have major feedback effects on climate in several ways. The presence of trees mask the high reflectance of snow, leading to warmer winter temperatures than if trees were absent (Bonan et al., 1992). Deforestation leads to decreases in temperature, even beyond the deforested area. Changes in species composition, as well as spatial distribution of vegetation, can result in both positive and negative feedbacks on climate (Price and Apps, 1995). Other feedback mechanisms on climate from changes in the boreal ecosystem include carbon sequestering and methane emissions (Wheaton and Wittrock, 1994). Formation of new ponds and flooding of existing peatlands will result in changes in the carbon pool and methane production, acting as a positive feedback on greenhouse gases (Bridgham et al., 1995). Fire is expected to increase with climate change in the boreal forest. This will result in an increased release of carbon dioxide during the fire, and higher decomposition rates for decades later will continue to release more carbon dioxide (Wein and deGroot, 1996).

Wildlife expected to be most affected by climate change in this region are species tied to semipermanent or seasonal wetlands. Amphibians in particular appear to be at risk, especially given their worldwide global declines (Wyman, 1991). Due to the need of many shorebird species for shallow wetlands, this group is also at risk.

It is estimated that 76 percent of Canadian terrestrial mammals and 60 percent of Canadian breeding bird species are forest dwelling (cited in Boyle, 1991). Since they are primarily insectivores, boreal nesting songbirds would be expected to be greatly affected by changes in forest composition, presumably with considerable variability among songbird species.

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CHAPTER 5

ADAPTATION TO CLIMATE

INTRODUCTION

The IPCC Working Group II (1996, p.5) defines *adaptability* as the "degree to which adjustments are possible in practices, processes, or structures of systems to projected or actual changes of climate". The range and effectiveness of adaptive strategies vary with the type of socioeconomic or natural system being considered. In general, most natural systems adapt slowly. However, technological advances offer increased adaptation options for managed systems such as agriculture, water supply and forestry. The application of a specific adaptation strategy depends upon factors such as the availability of financial resources, technology transfer, regulatory practices, among other factors.

Vulnerability can be defined as the extent to which climate variability may damage or harm a system (IPCC WGII, 1996, p.5). It depends on both a system's sensitivity and on its ability to adapt to new climatic conditions. Both the magnitude and rate of climate change are important in determining the adaptability and vulnerability of a system.

AGRICULTURE

Generally, food production is likely to decline in most critical regions as a result of global warming (e.g. subtropical and tropical areas), whereas agriculture in developed countries may actually benefit where technology is more available and if appropriate adaptive adjustments are employed. Since agriculture is also dependent on the natural resource base, a changing climate will require the adaptation of agricultural practices that accommodate the new climate while conserving the natural resource base.

The key for crop production to adapt to climate change is the predictability of the conditions. Thus, an understanding of the effect of the changing climate on land, water and temperature is required.

While temperature conditions may be favourable for growing new types of crops in the prairies, moisture deficits may preclude these new crops unless moisture deficits could be overcome through the use of irrigation.

In recent years many farmers have begun to diversify into speciality crops (e.g. mustard seed, dry peas and lentils). In some areas of extreme moisture deficits, extensive irrigation systems have also been developed. Livestock operations across the prairies are also diversifying with the introduction of buffalo, emus, and elk. Indigenous species, such as the buffalo and elk, are more adaptable to the climate of the prairies than traditional livestock, and might reduce some of the climate induced stress. More than half of Canada's beef cattle are now raised in western Canada, and hog production is becoming increasingly important.

Livestock is more resistant to climate change than crops because of its mobility and access to feed. Livestock production could be one of the key methods for farmers to adapt to climate change through diversification of their farming mix.

Government policies have a significant impact on current agriculture. Many policies of the past have not considered the need for adaptation, because it was not viewed as an issue. Although the agricultural sector is able to respond and adapt to changes in climate, government will play a role in how the sector adapts and how quickly. Government compensation, subsidy and assistance programs provide some form of economic and social security. However, if farmers on an individual level are always able to access government assistance when faced with climatic catastrophe, there is no incentive to change agricultural practices to match the climatic reality.

Current shifts in agriculture policy are starting to allow more flexibility in production, not only in techniques, but also in products. The focus of the Canadian Adaptation and Rural Development Fund has been to assist rural communities and farmers in adapting to changes in economic policies. While the program is not aimed specifically at climate change, there is potential to use it to have agriculture adapt to more than just economic policies. At the moment, however, the issue of climate change is viewed more from the mitigation perspective, in terms of agriculture's capacity to reduce greenhouse gas emissions and act as a carbon sink. Unless there is a substantial shift in the thinking regarding climate change and agriculture, the economic policies designed to help facilitate adaptation to changing global economic conditions may turn out to be a missed opportunity.

Policy adaptations could include reforming subsidies to reflect actual risk from climate; crop assistance programs could be linked to soil conservation; rural education systems could be strengthened to encourage sustainable land use practices; taxing water by volume for irrigation purposes or encouraging water conservation laws (Chiotti, no date).

Given the increasing pressures on water resources, many of the irrigation and water use policies will need to be reviewed as well. Decreasing availability of water for all users on the prairies will lead to conflicts as producers compete for irrigation water with other uses such as recreational, municipal and industrial.

One prediction is that there could be benefits associated with climate change, with a potential increase in agricultural production as favourable agro-climatic conditions expand northward in the Prairies. Such an expansion, however, would be tempered by the capacity of northern soils to sustain commercial agriculture.

FOREST ECOSYSTEMS

The western boreal forest is particularly sensitive to direct effects of climatic changes such as drought and indirect effects such as fire and insect disturbances. While the development of adaptive strategies regarding climatic change and variability appears to be in its early stages, some research does exist.

Changes are anticipated for the boreal forest, and adaptive strategies must be developed and tested. Changes may be subtle for some time, until ecological thresholds are reached, feedbacks intensify, or until disturbances occur. Neither will changes be easy to predict in most cases. Complex interactions, feedbacks, and nonlinear relationships will cause surprising results. Therefore adaptive strategies need to be robust and flexible.

Forests will be forced to migrate to keep up with the shifting climatic zones. Each species has different tolerances, genetic variances, and dispersal rates, so each will differ in its adjustment to the changing environment. Therefore ecosystems will not migrate as a unit in response to shifting climatic zones. The results could be new assemblages and new ecosystems (e.g., Singh and Wheaton, 1991). The success or failure of migration depends on many interacting factors, one of the most important being the rate of climatic change. A rapid rate of climatic change beyond the immediate adaptive range of many boreal tree species will result in increased failures in regeneration and restocking efforts in harvested areas.

Price and Apps (1995) report that a suite of predictive models is being developed to better assess short-term (50 to 100 year) transient ecosystem dynamics and their implications for management and policy. The models are based on field studies of past dynamics and current processes of the boreal and tundra biomes. These models will start to provide answers to many policy-relevant questions concerning current and possible future interactions between the boreal ecosystems and the global environment.

Neilson (1993) suggests that forests could undergo significant drought-induced decline and dieback. Also, drought-stressed trees are more susceptible to other disturbances such as insects and fires. Management of such forests and many other adaptive strategies, such as thinning for example, would be required to minimise losses.

The greater likelihood of fire hazard due to increasing drought frequency affects forest management costs to suppress or manage these disturbances. These expenditures form a large share of total forest management outlays. The average shares of total forest expenditures for protection from pests and fires were 63 percent and 36 percent for Saskatchewan and Alberta, for example, for 1988 to 1993. In the future, control expenditures will have to increase significantly or much larger areas will be affected by disturbances (Rothman and Herbert, 1997). Recommendations from the Pacific Northwest Forest Management Conference (Wall, 1993) for dealing with fire include managing stands and landscapes to reduce the likelihood of crown fires and large area fires, managing forest fuel, prescribed burning, preserving and enhancing biodiversity and managing forest landscapes that are becoming increasingly fragmented.

Binkley and van Kooten (1994) discuss the policy questions and the co-evolutionary development of the climate, terrestrial biosphere and the forest sector. They identify several gaps in research regarding adaptation and the development of policy options. They found that none of the studies examined explicitly traced the effect on the forest of adaptive changes such as those induced by policy. Promising policy options include carbon tax and materials policies. They emphasise the importance of including the non-timber aspects of forests in analyses because these values exceed the timber values by wide margins in many settings. Also, the non-timber aspects may be less able than forest industries to adapt to a changing climate.

Considerable investments are being made in reforestation, management and harvesting of forests, and in forest-based industries and communities. Climate change has implications for the costs and type of forest management and investments. For example, seedlings currently being planted will only reach about half of their harvestable age by about 2030 AD. At this time, they would be growing in a changed climate that may be more or less suitable to them and likely be exposed to a higher risk of disturbances. Maini (1990) writes that strategies to protect such investments should be developed. If climate estimates are correct, within 25 years we will have to deal with a range of new and complex issues around forest disturbances, vegetation competition, and the adaptation of harvest machinery and equipment. To compound the problem, the forest sector needs a longer lead-time than many other sectors to address issues determining the growth, health, and survival of forest ecosystems (Maini, 1990).

Binkley and van Kooten (1994) provide a recent concise summary: “The forest products industry can adapt to ecosystem changes by salvaging dying trees, replanting with better-adapted genotypes or species, or moving to those places where timber becomes more abundant.” They are less optimistic about adaptation for non-timber aspects, such as biological diversity. Rothman and Herbert (1997) suggest adaptation options such as using exotics on the southern edge to compensate for the productivity decline. Such an option may be useful to the forest industry, but the impacts on the non-market values, such as recreation, are also important to consider. The introduction of exotic species also could be of concern with respect to impacts on biodiversity and ecosystem health.

Adaptive actions that deal with climatic change and have other benefits, such as improving forest health and productivity, are recommended. A list of these possible “no regret actions” from the Pacific Northwest Forest Management Conference includes implementing uneven forest age management, maintaining an over-story cover, managing for several species, altering harvesting regimes to protect soils and maintain productivity, managing forest fuel build-up, and developing silvicultural alternatives to fire’s role in ecosystems (Wall 1993). These actions attempt to mimic natural processes.

Management of the forest for non-timber and non-market concerns is also required and should be modified to deal with climatic change. These issues include carbon storage, water quality and quantity, soils, air quality, and biodiversity. Conflicting competing demands will be increasingly imposed on the forest and will require innovative management responses and the application of much more knowledge than we currently have. Adaptation strategies will have to include all aspects of the forest ecosystem with harvesting, reforestation, utilisation, and protection strategies. Other interests include wildlife and fisheries, recreation, and communities (Hall and Carlson 1990).

Management to protect the forest from stress will be required including (Hinckley et al. 1993):

- maintaining landscape corridors, promoting landscape patterns that reduce the spread of disturbances
- protecting photosynthetic capacity and soil fertility at the stand level by protecting habitats required by natural enemies of forest pest
- maintaining or improving biodiversity

- maintaining or restoring tree vigour through practices including thinning, and
- avoiding clear cutting harvests to keep some cover of mature trees.

ENERGY

Adaptation to climate change will occur whether or not the decision is made consciously. The risk of taking a reactive response to change is the inability to take full advantage of that change and potentially allowing the economy to suffer from the ensuing socioeconomic problems. Climate change has the potential to alter land use patterns on the Prairies with the associated changes to habitation patterns. Understanding the impacts will allow the Prairies to take advantage of the positive aspects of change and minimize the negative consequences, particularly as they relate to the energy sector.

From an energy perspective, therefore, it will be necessary for energy decision makers and planners to understand not only the direct impacts of change on energy production and distribution functions, but also the effect on energy demand and distribution of the numerous adaptive strategies that will be implemented by other sectors of the economy. In other words, understanding the decisions made by energy users as they adapt to change will be important to energy planning.

It should be noted that one of the adaptive strategies that could be employed by industry and individuals is mitigation through actions to reduce fossil energy consumption. This, in itself, will result in the need for the energy sector to adapt to changes in energy demand.

The Prairies are characterized by cold winters and hot summers with the associated need for effective space conditioning of buildings. Because of the need for comfort in both work and living accommodation, buildings tend to be constructed to be relatively energy efficient. This does not mean that improvements are not possible or desirable, rather that the starting point for efficiency is generally higher than in other parts of Canada.

The production and use of fossil fuels creates the majority of greenhouse gases on the Prairies and activities in energy efficiency and conservation are promoted as the primary means to combat potential climate change.

Many energy utility companies, such as Manitoba Hydro, have adopted strategies to manage their ongoing operations to adapt to climate variability (Raban, 1991). These adaptive strategies will help to address the issue of climate change. For example, some of the actions implemented by Manitoba Hydro include:

- planners have re-examined the long range load forecast. They calculated the change in load with different climatic change scenarios for median and extreme cases. The load shift from winter to summer resulted in increases in dependable energy.
- system expansion planning was examined in light of climatic change. Results indicated that thermal plants become more suitable with increased warming, but hydro plants remain more economic, in general. However, increasing thermal capacity would come at a cost of increased carbon dioxide emissions and increased global warming feedback (G. Schaefer, personal communication, July 1997).
- improved capability to model the effects of icing on conductors. Weather stations are used to detect line icing conditions. This type of monitoring will be required to a greater extent with climatic warming.
- evaporative loss will become an increasing problem with climatic change. Research into improved methods of calculating evaporative demands is being sponsored.
- criteria for firmness of energy supply are being examined. Severe droughts, such as the 1987-1990 event are critical from an operating perspective.
- ice booms are being installed and tested. This type of work will become even more critical with increasing climatic change.

Adaptive strategies being considered by Manitoba Hydro include:

- developing a contingency plan for demand side management in the event of energy shortages.

- cooperating with other agencies to increase and to improve the exchange of climatic change related information.
- allocating resources for in-house experts to evaluate the probable effects of the most likely climatic change scenarios on the drainage basins.

INSURANCE

Insurance companies reduce the “scope” of their losses by increasing premiums and/or deductibles, reducing or withdrawing coverage altogether, or by making the underwriting of risk conditional on certain actions being taken by the policy holder (Nutter, 1996; Swiss Re, 1994; Deering, 1994). If catastrophic weather events become more frequent and possibly less predictable, insurance companies may be faced with no other choice but to withdraw coverage especially for policy holders who are located in vulnerable areas.

Crop insurance in the Canadian prairies is administered and supported by the three provincial governments. As such, producer premiums may increase, or taxpayers will be expected to carry the increased expenditure on crop insurance. Alternatively, the increased expense may be shared by both the producer and the taxpayer.

Further socio-economic implications of climate change and its effects on the insurance industry are that the collapse of the insurance and financial sectors could lead to the loss of jobs (Nutter, 1996). Without adaptation on the part of all concerned it is possible that such a scenario could occur. Some hold even more drastic opinions of what will happen if we do not adapt and the possible effects of climate change are not built into the insurance industry’s assessment of risk. Rudolf Kellenberger, a member of Swiss Re’s executive board wrote in a Swiss Re report: “The more quickly and radically the global climate changes, the more extreme weather patterns could cause damage which not only pose a threat to individual citizens, families and enterprises but could jeopardise whole cities and branches of the economy - on a global scale - entire states and social systems.” (Swiss Re, 1994). Such economic devastation, if it should occur, would lead to loss of livelihoods, poverty and, in extreme cases, homelessness.

The insurance industry is not taking the possibility of climate change lightly. In November 1995 the United Nations Environment Programme Insurance Initiative was launched with a Statement of Environmental Commitment by the Insurance Industry. This has been followed up by a position statement submitted by the industry to the Climate Change negotiations in Geneva, 9 July 1996. In this statement the industry calls for early and substantial reductions in greenhouse gas emissions; further scientific research that establishes what level of greenhouse gases is likely to be dangerous; the establishment of a transparent framework of political, social, and economic measures that will promote sustainable development while taking into account the risks of climate change; and the position of the insurance and reinsurance sector to be represented when discussing or negotiating possible solutions to the problem of climate change (UNEP III, 1996).

On less of a policy level and more of a practical level, some insurance companies have invested and are investing in environmentally safe technologies thereby creating a kind of climate venture fund. Another possibility is to reduce investment in companies that contribute to greenhouse emissions. A precedent has been set for dumping stock in oil and coal companies for instance by health insurers who’ve sold their stock in tobacco companies. The industry is also lobbying for tighter building codes that improve energy efficiency and enable buildings to withstand the ravages of the weather (Deering, 1994; Flavin, 1994; Howard, 1995; Leggett, 1993).

RECREATION AND TOURISM

Recreationists have a degree of flexibility in their response (adaptation) to climatic variability and change. Traveling to alternative locations with favourable conditions, reducing participation when conditions are unfavourable or ceasing to participate in their usual activities, are all options that can be pursued. People also can undertake new activities or increase their involvement in other activities. Requirements for recreational activities may change with technological advances in clothing and equipment. The constraining factors will be free time and personal economic well-being (More, 1988).

WATER SUPPLY AND DEMAND

The Prairies have a long history of adapting to climate variability. The vagaries of an uncertain water resource, and competing demands, have necessitated various engineering solutions to the variable water supply.

For example, large reservoirs have been constructed on virtually every major river system in the grasslands region. These reservoirs capture spring runoff for delivery during times of drought and reduce flooding during times of peak flows. Saskatchewan has about half of the approximately 770 dams in the Prairie Provinces and over 80 percent of the reservoir capacity (Environment Canada, 1991). Most of these reservoirs serve multiple objectives, such as for irrigation, power production, recreation, flood protection to downstream communities, and interbasin transfers of water.

Another adaptation strategy used to improve domestic and agricultural water availability in the region by storing spring runoff is the construction of farm and community dugouts. It is estimated that over 110 000 dugouts exist in the prairies (Environment Canada, 1991). During severe drought years when spring runoff is low, farmers and ranchers are forced to pump water into their dugouts from more reliable sources, such as rivers and lakes.

Many rural areas within the prairies also rely on groundwater supplies either entirely or as a supplement to surface water supplies. Regional pipeline distribution systems are also becoming a common adaptation strategy.

Various water management policies and legislation exist to address the geographical imbalance in water supply and demand. For transboundary (international, interprovincial and provincial-territorial) river systems there are formal agreements which specify how much water can be used within each jurisdiction. For example, a Master Agreement was signed in 1969 between Canada and the Prairie Provinces that defines the water allotment for each province. A major provision commits Alberta to pass one-half of the natural flow arising in or flowing through Alberta to Saskatchewan. Saskatchewan has a similar commitment to Manitoba. There are also policies in place to encourage farmers to maintain wetlands for wildlife purposes and other policies which promote the construction of new wetlands and enhancement of existing ones.

WILDLIFE AND BIODIVERSITY

Parkland wetlands are more sensitive to temperature than are Grassland wetlands (Larson, 1995). This may become important to nesting waterfowl if more birds shift to breed in the Parklands, as grasslands advance farther north. Waterfowl production is related not only to the number but also to the type of prairie wetlands (Diamond and Brace, 1991), usually small seasonal and semipermanent ponds, which are likely to be affected by climate change.

The speed of climate change is expected to outstrip the ability of tree migration to respond (adapt) and current landscape practices have created barriers to plant migration (Kurtz and Sampson 1991). In Minnesota, Davis (1990) listed several factors adding to limited dispersal of tree species, including increased deer browsing (limiting reproduction), a decreased seed source due to logging, and less old growth to produce dead logs that protect seedling growth. She noted that dispersal would be even more of a problem for wind-dispersed herbs. Since humans can plant economically useful tree species in disturbed habitats, Davis (1989) expected natural areas to be most affected by lags in vegetation responses to greenhouse warming.

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CHAPTER 6

OPPORTUNITIES FOR FURTHER RESEARCH

INTRODUCTION

When the Canada Country Study was initiated in the summer of 1996, the authors of the regional sectoral assessments reports (attached as appendices to this document) were asked to consider the following five questions:

1. *Why might climate change be a problem for this sector?*
2. *What do we know about the connection between current climate variability and this sector? How sensitive might this sector be to a warmer and a wetter or drier climate?*
3. *What may occur in this sector of the economy or the environment if a global warming occurs over the next 50 to 80 years?*
4. *So what? Will these changes affect people in any way?*
5. *Will other effects, for example population growth or forest over-harvesting, overwhelm any climate change impacts on people? Or will climate change exacerbate these other effects?*

In addition, the authors were asked:

> *What should be done? Is more research needed on climate change impacts, and if so, where should we concentrate?*

As summarized in this report, considerable scientific literature related to climatic variability and change within the Prairie Provinces has accumulated, particularly over the past decade, but the quantity and quality of this research is highly variable from one economic sector or issue to another. Our understanding of the science is sometimes quite cursory and much research still needs to be undertaken to fill in some of these major gaps in our knowledge. This chapter identifies some of those deficiencies, and in so doing, provides guidance for new research initiatives which will be undertaken in the years ahead.

AGRICULTURE

On a global basis, climate variability and change may have an overall negligible effect on total food production (IPCC WGII, 1996). However, the regional impacts may be substantial and variable, with some regions benefiting from an altered climate and other regions being adversely affected.

Smit et al. (1996) and Chiotti et al. (1997) identify several questions which should be considered in future research on climate change and variability impacts on prairie agriculture:

- What are the attributes of climate to which agricultural systems respond?
- Why do responses differ, and what characteristics of farming make certain types of regions more vulnerable or adaptive than others?
- What non-climatic conditions influence the propensity to adapt?
- What role do crop insurance, subsidies and technological development play in influencing adaptations in farming systems?
- What are the constraints on and incentives for adaptation in the future?
- How sustainable are land management responses to climate change?
- How can agriculture become more sustainable in the event of climate change?

Specific studies on agriculture and climate change might include:

- A vulnerability analysis should be done for all three prairie provinces of the effect of climate change on agriculture and the second round effects on the other sectors of the economy. An attempt should be made to quantify the costs and benefits.
- General equilibrium models should be integrated with climate change and agricultural models in order to try and take the dynamic nature of things into account.
- Further research is needed on farm-level decision making, examining the role of climate change variables vis-a-vis societal and other forces in influencing land management adaptations.
- Although some models predict a northward movement of agriculture, further research is needed to determine the suitability of these soils to a shift in agriculture.
- Based on what climate variability and change can be expected on the prairies and how it will affect agriculture, agricultural policy needs to be analysed and adjusted so that it acts as an incentive to farmers to adopt the appropriate management strategies and agricultural practices for the new climate reality.
- Further research is needed to determine the indirect effects of climate change; specifically the impacts on agriculture elsewhere and the effect upon Canada's competitive position in the global marketplace.

FOREST ECOSYSTEMS

The global biosphere is clearly very sensitive to climatic perturbations, but our present understanding of the interactions among changes in climate, elevated carbon dioxide concentrations, and soil nutrient dynamics is limited. This seriously constrains our ability to build models to make confident predictions of the specific responses of forest ecosystems to expected climatic changes (e.g. Price and Apps, 1996). Responses of productivity, for example, are very variable, depending on climatic scenario and vegetation impact model used. It is clear, however, that research formulation and implementation, impact assessment, and adaptive strategy development regarding climatic change and variability appear to be in their early stages. Many key policy and research questions remain priorities.

The questions that guided the objectives of this work are far from completely addressed with the current available literature related to the western Canadian boreal forest. The literature reviewed emphasizes several main research, monitoring, and policy questions that require priority action. Sample questions include:

- What is the nature of the current interactions between climate and the boreal forest ecosystem? What critical monitoring needs are not being met? How fast are conditions changing?
- How should climate scenarios be developed to better reflect the range of possible futures?
- What are the likely effects of forest ecosystem changes on other sectors?
- What are the shorter to longer term (5 to 50 year) interactions expected between climatic variability, especially extremes such as drought, and the forest ecosystem? Currently, the lack of monitoring and research tools limit this understanding.
- What is the net effect of changes in growth and changes in disturbances over the long and short terms? Disturbances have a main role, especially in this study area, and the climate-disturbance models are mostly in their early stages of development.
- What adaptive strategies are available? What ones are required? How well do they work? What are the linkages with mitigation? What are their socioeconomic implications?.
- Is the southern boundary limited by moisture alone or by a combination of effects involving both moisture and fire?
- Vegetation has a feedback effect on climate. How does the distribution of forest and grassland affect the climate? How would changes in vegetation affect the evolution of the changing climate?

- Increased fire risk is expected with climatic warming scenarios. How can scientists provide quantitative estimates of fire risk for climatic change?
- What is the role of the biota in the global carbon cycle? We still do not understand the current role of forests in modifying the global carbon cycle. This uncertainty is reflected in the fact that 20 to 50 percent of the annual fossil fuel carbon cannot be accounted for and that forests are described as both sources and sinks, depending on the study.
- Biomass productivity and mortality are fundamental to determining the carbon dynamics of forests. There is an urgent need for improved knowledge of these processes (e.g., Shvidenko et al*.,* 1996). A large wild card appears to be the balance between climate-induced growth and disturbance (Tian et al*.,* 1995). Which will predominate, and where and when?
- What changes in the economic importance of the forest resource can be expected with the types of climatic changes foreseen? How sensitive is the forest industry to these changes? Would most of the effects be direct through changes in growth patterns or indirect through forest disturbances and changes in infrastructure (roads) and demographics or policies for greenhouse gas management?

Although much of the boreal forest is not managed, the amount of managed forest is increasing. There are many questions about the relationships among a changing climate, forest and management including:

- How can the forest be better managed in order to reduce the negative effects of climate and increase the positive effects?
- Will future management be able to offset the projected negative climatic effects?
- What types of future management are required to cope with a changing climate? How practical and economical are they? Are they appropriate to the study area?
- Do we have sufficient management knowledge and tools? For example, genetically improved stock would be needed for productivity with increased droughts (Shelley, 1997 personal communication).

Several general research recommendations include: climate forecasting and scenario development, forest response forecasting (physiology, reforestation, tree variations, pollutants, fire, insects, diseases, forest decline), monitoring, mitigation, carbon budget, and socioeconomics.

The early stage of the modelling framework used to assess the likely fate of the world's forests severely limits impact and adaptation assessments. IPCC WG II (1996) states that a consistent and comprehensive research strategy is needed to improve understanding of:

- the ecophysiological response of trees to changing climate and carbon dioxide concentrations;
- the relationship between tree growth and transient forest dynamics; and
- the influence of a changing forest on the global carbon budget and its feedback. Process-based terrestrial biosphere models of ecosystem dynamics are required to improve the overall modelling framework which would allow better assessments of forest interactions with climatic change.

ENERGY

The research undertaken and literature published on the subject of climate and energy interactions (especially climatic change aspects) in the Prairies is sparse. Therefore, recommendations tend to be very general. In addition, since the focus of attention has tended to be the electrical sector, a broadening of prairie work is required.

It has been assumed that the energy sector is most sensitive to space conditioning loads (e.g. IPCC WGII, 1996). However, an overview sensitivity analysis has not been performed. Such work would confirm assumptions specific to the study area and would also be very useful for priority setting. Also, Research on each topic presented in Table 15 (Chapter 4) regarding possible impacts should be considered.

Following are examples of questions extracted from the literature:

- What are the sensitivities of different parts of the energy sector to climatic change? How do these compare to the sensitivities of other sectors?
- What are the effects of droughts and floods on the energy sector. What implications would the findings have for future effects and adaptations in a changing climate?
- What is the extent of knowledge of indirect effects - e.g. with changing residential demand (e.g. space conditioning), and can the industrial demand be met?
- What are the best quantitative and qualitative models for use in estimating impacts and testing adaptive strategies?
- What are the interactive effects of climate change and how does this affect adaptation? For example, energy loads are affected by agricultural energy use demands. Agricultural energy uses are sensitive to climate, especially extremes.
- It is often assumed that climatic change will occur gradually, which would make adaptation easier. There is, however, some indication that climate has undergone large changes in decades or less. How would the rate of change affect impacts and adaptation?

With regard to policy, the following questions have been raised:

- How adequate are current policies and practices in responding to changing climate?
- What infrastructure effects can be expected? For example how will continued permafrost thawing affect pipelines and other energy related infrastructure?
- What is the balance between adequate adaptation and mitigation? What are the linkages between adaptation and mitigation? For example, how will mitigation policies affect the capability to adapt?

Based on the above analysis and general questions gleaned from the current literature, research and the associated policy analysis should specifically reflect the following priorities:

- There is a need to monitor and to assess the timing and risk of climate variation and change occurring globally and in the three Prairie provinces.
- Once the risk is understood, the likely impacts of change on agriculture, water supply, forestry, transportation and other sectors can be assessed.
- These changes will have a direct impact on the energy production and distribution industry. Depending on the nature and assessed risk of these changes, a preparation and response strategy can be developed by industry to accommodate future changes.
- An aggregation of the adaptive strategies of the other sectors of the economy will provide an insight into the likely demographic and industrial changes that will occur. This would provide an understanding of areas of competition for resources, particularly water, and where the energy will be required.

INSURANCE

Literature on the insurance industry and climate change on the prairies (especially the Canadian prairies) is limited. Also, the vast majority of the discussions focus only on property insurance. Since agriculture is one of the most important economic activities on the prairies, a greater understanding of the implications of climate change for the crop insurance industry is required. There is also very limited information about the interaction between health and climate change and variability. Impacts on health will inevitably be passed on to the insurance industry. The greatest problem facing insurers right now - regardless of where in the world they operate - is that of assessing risk related to climate change.

Further research would include:

- Improved understanding of regional climate scenarios. The resolution of current GCMs is still too coarse to be able to provide insurance companies with the kind of information that they need for setting fair and realistic premiums in the face of climate change.
- More study needs to be done on the kinds of risk that insurance companies can expect to incur when covering climate

related damages on the prairies. Can insurance companies expect to cover more hailstorms? Will drought become a more frequent factor to contend with? Are crops more susceptible to pests as a result of warmer weather? Will health ailments increase with higher temperatures and the possibility of more dust storms, for example? Perhaps an analysis of the existing paleoenvironmental record will provide the critical data concerning the frequency and magnitude of extreme events that is necessary to the industry (D. Lemmen, personal communication, July 8, 1997).

- The links between scientific, financial and statistical analyses and the use of remote sensing and other techniques need to be developed in order for insurance companies to assess their risk accurately and project future losses, and
- The possible effects of climate change on the health of individuals in the prairies needs to be evaluated. This information should be built into any decisions that are made with regard to reforming the health system.

RECREATION AND TOURISM

Very limited research has been done on this topic specifically. Further research is required in the following areas:

- Improve regional climate change scenarios,
- Improve our understanding of the economic costs of creating favourable recreation conditions,
- Conduct a comparative study of competing attractions in places bordering on the region and the costs of engaging in these activities,
- Develop new management strategies to take into account the changing resource base in its effect on vegetation, wildlife and recreational choices, and
- Assess resource conflicts due to competition for scarce resources, such as water, and establish legislation or policies to resolve these conflicts.

WATER SUPPLY AND DEMAND

Climate models that are capable of predicting changes at the regional level, both spatially and temporally, must be developed to assess the impacts of climate change on water supply and demand.

A comprehensive assessment of the likely effects of global warming on water supplies and demands should be undertaken. Appropriate mitigative and adaptive strategies should be formulated and implemented.

Changes to wetlands should be tracked with a coordinated ongoing monitoring program. More research should be done on wetlands ecology in its broadest sense. This would include the role of climate and climate change, and interactions with wildlife and fish. Important environmental indicators that can be used to help track changes in wetlands should be identified. Wetland ecosystems need to be evaluated, in both economic and non-economic terms. Land use and other programs and policies that affect wetlands should be updated to incorporate wetland conservation and restoration as objectives so as to try to assure sustainability in a changing climate. Every effort should be made to heighten public awareness of the general values of wetlands and thus to improve public support for sustaining wetlands in a changing climate (Wheaton et al., 1992).

There will have to be further research in socioeconomic adjustments and impacts in areas such as municipal water use, tourism and recreation, agriculture and power generation under a warmed climate (Cohen and Allsopp, 1988, Thomas, 1990, cited in Wheaton et al., 1992).

A large part of the prairies is dependent on snowmelt runoff from the Rocky Mountains. Research is required to assess the impact of climate change on the magnitude and timing of mountain runoff.

AQUATIC ECOSYSTEMS

Although issues surrounding climate change, and global warming in particular, are increasingly the subject of study, the impacts of such change on freshwater systems have received considerably less attention (Carpenter et al., 1992; Vitousek, 1994). This lack of study is particularly apparent within the Prairie Provinces and the resulting information gap is especially significant in light of the fact that freshwater systems are critical to ecosystem sustainability and are tightly coupled to both climate and land use activities (Firth and Fisher, 1991; Carpenter et al., 1992).

Unfortunately, the relationship between climate change and flow regime is complex and poorly understood (Carpenter et al., 1992) and while the frequency, intensity and extent of disturbance (e.g., scour, flood, drought, etc.) is known to be a critical determinant of community structure in various systems, there is little consensus about the specific consequences of such disturbance (Resh et al., 1988).

An understanding of climate impacts on the hydrologic cycle is thus a crucial first step in determining the consequences of climate change for aquatic ecosystems. The challenge for researchers is to more explicitly link climate change to the hydrologic cycle and then to link this to the chemical and biotic structure and function of the ecosystem.

Climate change and the impacts resulting from such change is a growing issue and one which will be the subject of ever increasing research efforts for the foreseeable future. While considerable effort has already been invested in attempts to monitor, model and predict climate change, considerably less effort has been focused on investigations of the direct ecological impacts of climate change.

The challenge associated with determining the ecological impacts of climate change are daunting, the long-term data sets (such as that provided by the Experimental Lakes Area study of northwestern Ontario) required to investigate the impacts of climate change are rare, and the opportunities to undertake (or even continue) such studies are even rarer. It is possible to state that changes in temperature and precipitation in prairie aquatic systems will affect those ecosystem components sensitive to temperature and precipitation. However, such an observation is of little value. Attempts to be more predictive soon become mired in the complex nature of the relationships and the significant gaps in knowledge. An opportunity exists here for integrating short-term, intensive monitoring studies (such as ELA) with existing paleoenvironmental data and quantitative predictive models (D. Lemmen, personal communication, July 8, 1997).

Future research on the impacts of climate change in aquatic systems in the Prairie Provinces should first focus on developing predictive models capable of linking hydrologic processes to climate change. This work has already been initiated but must be further developed. Prairie aquatic ecosystems are largely defined and driven by hydrologic issues such as drought, flooding, precipitation and evaporation. An understanding of how climate change will affect these processes is the first step in understanding the ultimate impacts of climate change on aquatic ecosystems in this region.

A second major obstacle to assessing the impacts of climate change is an incomplete understanding of the ecology of these systems. This is not a criticism of the research that has been done but a recognition of the complexity of these systems. Even after three decades of concentrated research in the ELA many basic ecological relationships remain unexplained and many of the observed changes would not have been predicted. For, example changes in the hydrologic cycle, reducing DOC export and increasing UV-B penetration was not an intuitively obvious outcome of climate change.

It is essential, therefore, that continued research into the basic ecology of these systems be supported and encouraged. At the same time, many of the basic ecological studies already conducted on these systems could provide useful insight into the potential consequences of climate change. These studies should be synthesized and reviewed in this context.

Finally, climate change is but one element in a larger issue of environmental change and must be viewed in that context. No attempt to assess the impacts of climate change will be complete unless other forms of environmental change are accounted for. In the case of prairie aquatic ecosystems, stresses arising from the direct consequences of climate change are very likely to be exaggerated if other forms of environmental change (e.g., landuse and/or cover changes) are not controlled.

WILDLIFE AND BIODIVERSITY

Virtually all references to the effects of climate change on the Canadian boreal region discuss either the potential effects of changing boreal vegetation on climate, or potential effects of changing climate on vegetation Almost none discuss wildlife except to note potential changes in the frequency of forest insect pest outbreaks.

There is very little mention of potential effects of climate change on wildlife in western boreal forests. Singh and Wheaton (1991) note that global warming is likely to affect wildlife habitat, and that there is a potential threat to the survival of species confined to parks and reserves that could become habitat islands.

Prairie

Few studies directly involve effects of climate change on prairie wildlife or biodiversity. However, a number address responses of species to climate variability, notably drought. Few mammal studies were noted.

Studies examining the synergistic effects of UV-B radiation, water chemistry, and agricultural chemicals appear to be lacking for Canadian prairie amphibians. Ways in which climate affects waterfowl production are well known, but we need more information on factors affecting productivity and survival of nongame species. Due to the need of many shorebird species for shallow wetlands that are highly susceptible to climate change, this group is also at risk. The potential fate of semipermanent and seasonal wetlands under a changed climate needs to be addressed. If sufficient information exists on individual species (or species assemblages) and climate, species interactions, abundances and so on, lists of 'risk assessments' could be created for groups of animals and plants. For example, although the Long-billed Curlew is currently high on a list of birds potentially at risk of extinction (due to their decreasing habitat and low population numbers), this species might benefit from climate change, as its preferred habitat is dry, heavily grazed grassland.

Boreal

Although considerable literature has been published on potential effects of climate change on commercial tree species, very little work appears to have considered the fate of understory plants or wildlife. Ironically, 76 percent of Canadian terrestrial mammals and 60 percent of Canadian breeding bird species are forest dwelling (cited in Boyle 1991). Since they are primarily insectivores, boreal nesting songbirds would be expected to be greatly affected by changes in forest composition, presumably with considerable variability among songbird species. This must be addressed in particular, and lists of 'risk assessments' created for other boreal species as well.

PROXY RECORDS OF CLIMATE

Despite more than 40 years of scientific activity and hundreds of studies, there remain significant gaps in our understanding of the postglacial paleoenvironments of the Canadian prairie provinces. This is a very large region with considerable diversity from the subhumid to semiarid Palliser Triangle to the subarctic to high mountain landscapes. Research on the postglacial paleoenvironments of the subhumid southern Interior Plains should be encouraged, taking advantage of interest and expertise developed under the Palliser Triangle Global Change Project (Lemmen et al., 1993; Vance and Last, 1994).

The reconstruction of environmental history (hindcasting), irrespective of the proxy, is based on the understanding of natural systems and their relationship to climate; “the present is the key to the past”. Thus our interpretations of proxy data are only as good as the database of contemporary ecological, hydrological, meteorological and geological data. Paleoecology requires an understanding of the organisms that are preserved in sediments and the controls on species distribution and range. Paleolimnology requires various data on the physical and chemical characteristics of lakes, including the groundwater controls. The climatic forcing of geological processes can be reconstructed from deposits and landforms only with knowledge of the behavior of geomorphic systems. Therefore, a second recommendation is support for the monitoring of ecological, hydrological, meteorological and geological processes.

The monitoring of processes reveals the immediate responses of natural systems to hydroclimatic events, but only for current climatic conditions. Long stratigraphic records, on the other hand, uncover the extremes and periodicity of environmental change, but the generally low resolution limits the inference of climatic controls. Thus, intermediate spatial and temporal scales seem best suited for the reconstruction of paleoclimate with reasonable resolution, but also over sufficient time that both climatic variability and change are detectable. Proxy records from the past millennium offer the best opportunity to resolve climatic variability or at least the range of climatic extremes. Presently there seems to be a gap between the tree ring records of annual resolution, but short duration (centennial), and the lake sediment records of long (millennial) duration but generally low resolution (decadal to centennial). Therefore a third recommendation is that research be encouraged to extend the length of tree ring chronologies and the resolution of stratigraphic work such that overlap of the two databases can provide a high resolution record for the past millennium.

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APPENDIX A

AGRICULTURE AND CLIMATE CHANGE:

A PRAIRIE PERSPECTIVE

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A PRAIRIE PERSPECTIVE

Allen Tyrchniewicz
International Institute for Sustainable Development
Winnipeg, Manitoba

and

Quentin Chiotti
Environmental Adaptation Research Group,
Institute for Environmental Studies
University of Toronto

EXECUTIVE SUMMARY

On a global basis, climate variability and change may have an overall negligible effect on total food production. However, the regional impacts are likely to be substantial and variable, with some regions benefiting from an altered climate and other regions being adversely affected.

It is undeniable that Prairie agriculture has had an explicit history in terms of its vulnerability to the vagaries of climate. The drought of the 1930s, and most recently 1988, illustrates the sensitivity of agriculture in this region to severe moisture deficits. Combined with recent floods, the ever presence of hail damage, and other climatic events (e.g. early autumn frost), the historical record and current conditions underscores the variability of climate and the negative effects from extreme weather events. Combined with estimates that future droughts under climate change could be both more frequent and severe than in previous years, the vulnerability of agriculture and its capacity to adapt demands closer attention.

Adverse effects from climate change can be reduced through successful adaptation, which would likely be less than the cost of the impacts that would otherwise occur without adaptations. Further, we can anticipate that there could be significant implications arising from climate change for agriculture in Canada, both directly upon our food production, and indirectly from the impacts upon competing agricultural regions in other countries. One prediction is that there could be benefits associated with climate change, with a potential increase in agricultural productions as favourable agro-climatic conditions expand northward in the Prairies. Such an expansion, however, would be tempered by the capacity of northern soils to sustain commercial agriculture.

While temperature conditions may be favourable for growing new types of crops in the prairies, moisture deficits may preclude these new crops as an adaptation option. However, in order to adopt these new crops, moisture deficits could be overcome through the use of irrigation (also an adaptive strategy). Decreasing availability of water for all users on the prairies will lead to conflicts as producers compete with recreationists, household users, electrical utilities, and the manufacturing and other industry for water for irrigation.

In terms of the effect of changing crop mixes and revenues on the rest of the prairie economies, other sectors will be affected by expenditures for farm inputs and consumer goods and services. Discretionary expenditures change in direct response to changes in cash flow, hence those scenarios that produce a negative effect on prairie agriculture will pass on those negative effects to other sectors too but to a lesser degree.

INTRODUCTION

Agriculture is an economic activity that is highly dependent upon weather and climate in order to produce the food and fibre necessary to sustain human life. Not surprisingly, agriculture is deemed to be an economic activity that is expected to be vulnerable to climate variability and change. The vulnerability of agriculture to climate variability and change is an issue of major importance to the international scientific community, and this concern is reflected in Article 2 of the UNFCCC, which calls for the:

> ...stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent serious anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to: (i) allow ecosystems to adapt naturally to climate change; (ii) ensure that food production is not threatened; and (iii) enable economic development to proceed in a sustainable manner.

On a global basis, climate variability and change may have an overall negligible effect on total food production (Parry and Rosenwieg, 1994); however, the regional impacts are likely to be substantial and variable, with some regions benefiting from an altered climate and other regions adversely affected. Generally, food production is likely to decline in most critical regions (e.g. subtropical and tropical areas), whereas agriculture in developed countries may actually benefit where technology is more available and if appropriate adaptive adjustments are employed.

In terms of undertaking a national assessment of climate change impacts on Canadian agriculture, this sector has received considerable attention relative to other resource sectors. There has been a significant amount of research and studies directed at climate change and agriculture in Canada, and much of this literature has already been compiled in annotated bibliographic form (e.g. Wheaton, 1994). Further, agriculture has received attention on a regional basis (e.g. the MBIS, the GLSLB Project, and the proposed Prairie Climate Impact and Adaptation Study), and some areas, such as parts of the Prairies, have been examined in terms of its palaeo record (the Palliser Triangle Study), and current and future climate (the Nat Christie Foundation Project in Alberta). Although there is a substantive body of literature focusing upon climate change and agriculture, there continues to be a wide range of opinions regarding scenarios of future impacts. In the Prairies, for example, which is an agricultural area of significant global, national and regional importance, the most recent IPCC Assessment Report presented a guardedly optimistic, and yet foreboding appraisal:

> Increased agricultural production on the Prairies is a possibility with higher temperatures and CO_2 levels, provided adaptation measures are undertaken and adequate rainfall occurs. However, some models project more frequent and serious drought (Canadian Climate Program Board, 1995, p. 5).

Notwithstanding this appraisal, it is undeniable that Prairie agriculture has had an explicit history in terms of its vulnerability to the vagaries of climate. The drought of the 1930s, and most recently in 1988, illustrates the sensitivity of agriculture in this region to severe moisture deficits. Combined with recent floods, the ever presence of hail damage, and other climatic events (e.g. early autumn frost), the historical record and current conditions underscores the variability of climate and the negative effects from extreme weather events.

Given the historical sensitivity of Prairie agriculture to climate, the uncertainty which exists in our scenarios, and the economic and social importance of this sector, there is a strong need to improve our understanding of climate change impacts and the adaptability of Prairie agriculture. As a first step to address this need, the purpose of this paper is to present a brief overview of the literature on agriculture and climate change impacts and adaptation in the Prairies.

The paper is organized into 5 sections and begins with a brief description of agriculture in the prairies, establishing the biophysical and socio-economic context. The next section presents an historical synopsis of agriculture and climate, highlighting the adverse impacts associated with extreme moisture deficits, or droughts. In section IV, the discussion focuses upon climate change impacts, and is organized following the research protocol: (i) agroclimatic conditions; (ii) crop yields; (iii) livestock production; (iv) economic impacts; and (v) agriculture policy. Issues influencing future impacts and adaptations are discussed in section V, specifically changes in socio-economic conditions and agricultural policy, exports and comparative advantage, and sustainable development. In the conclusions, knowledge gaps are identified and a list of recommendations and questions for further research is presented.

PRAIRIE AGRICULTURE: THE BIOPHYSICAL AND SOCIO-ECONOMIC CONTEXT

Prairie agriculture is located in a physiographic region known as the Western Interior Basin (Plains) and includes the northern portion of the Great Plains ecozone. The natural vegetation of this region is primarily grassland, extending southward from the Boreal Forest into a transition zone of Aspen Grove to Mixed-grass Prairie and Short-grass Prairie, with the northern tip of the True Prairie grassland extending into south eastern Manitoba. The soils of the interior plains are quite fertile, made up of Brown Chernozemic, Dark Brown Chernozemic and Black Chernozemic soils (Watts, 1967). In terms of climate, the agricultural regions experience relatively long winters, short summers and low precipitation. Clear skies and warm temperatures generate favourable growing degree days, ranging from 1700 - 1800 in Manitoba, with Saskatchewan and Alberta receiving on average 100 - 300 less. Although precipitation tends to be relatively low, fortunately for agriculture most of the precipitation falls during the growing season, and typically during the month of June when crops can best use the moisture. Annual precipitation ranges from 400 mm - 600 mm for Manitoba, whereas Saskatchewan (300 mm - 500 mm) and Alberta (300 mm - 500 mm) tend to receive slightly less amounts of rainfall. Moisture deficits, however, tend to exist in most agricultural regions, ranging between 150 - 250 mm, and are particularly high in an area known as Palliser's Triangle. Swift Current, for example, typically experiences a moisture deficit of approximately 400 mm. Extreme weather events such as drought, tornadoes, flooding and hail tends to be a common occurance throughout the Prairies, although the frequency and severity of these events tends to be regionally variable. For instance, the corridor between Red Deer and Calgary is known as 'hailstorm alley', experiencing some of the most numerous and severe hailstorms in the world (Phillips, 1990).

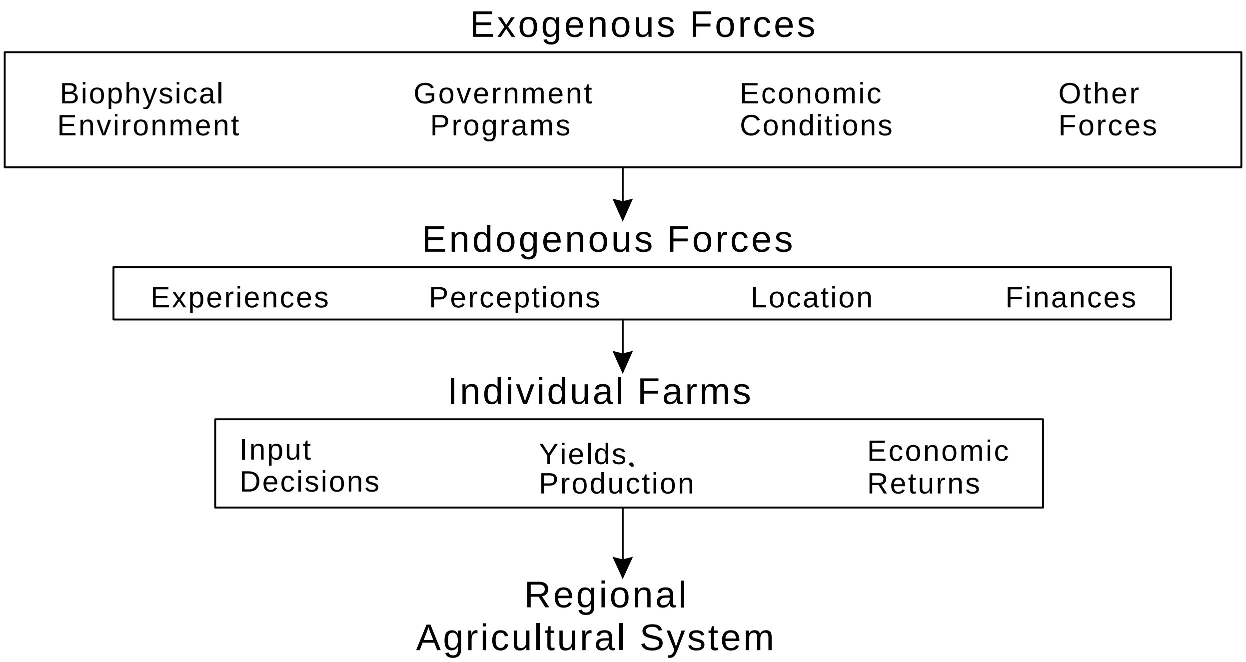
Due to this combination of rich soils and favourable agro-climatic conditions, most of the area where agriculture is now practiced are on soils classified according to the Canada Land Inventory as Classes 1, 2 and 3. Generally, these soils have few limitations to crop production, or where moderately severe limitations exist (Class 3), they can be overcome with good management practices (Statistics Canada, 1984). In the Peace River district, where soils have more severe limitations and agro-climatic conditions are less favourable, hay and pasture dominate agricultural activity. Generally, the location of agriculture, and particularly crop production, is closely correlated with soil suitability, reflecting the importance of soil and climate in determining where and what crops are grown.

Although grain production has historically been associated with Prairie agriculture and continues to account for the majority of production, in recent years many farmers have begun to diversify into speciality crops (e.g. mustard seed, dry peas and lentils). In some areas of extreme moisture deficits, extensive irrigation systems have also been developed. For example, almost 500,000 ha of farmland is currently under irrigation in southern Alberta, producing a wide variety of crops including grains, pulse crops, corn, sugar beets and vegetables. The raising of livestock is also an important agricultural activity, particularly in terms of cattle. More than 50 percent of Canada's beef cattle are now raised in western Canada, and much of this is concentrated in Alberta. Hog production is becoming increasingly important in the Prairies, while under supply management regulations, the region also produces most of its requirements for poultry, eggs and dairy (fluid milk) products. Livestock operations across the prairies are also diversifying with the introduction of buffalo, emus, and elk. Some farmers have recognized that the indigenous species, such as the buffalo and elk are more accustom to the climate of the prairies, than traditional livestock, and might reduce some of the climate stress.

Farming is an activity that is influenced by many exogenous and endogenous forces (Figure 1). Exogenous forces, those beyond the control of the farmers, have a major influence on the prairie farms. These forces include such things as the biophysical environment, government policy, and economic conditions. The endogenous forces are those the farmer has some control over. They include: the farmer’s experience, perceptions, location of the farm, and finance. Combining these forces results in a vast array of individual farm decisions, and when the results of each farm are combined, leads to the regional agricultural system. The agricultural system is also part of a broader agri-food system, whereby modern commercial agriculture is one stage in a food production process linking farmers and consumers via a system of processors, distributors and retailers. The agri-food system is both complex and differentiated across the Prairies, with some regions more dependent upon grains and other regions more diversified into livestock production and/or value added processing.

Canadian agri-food exports are an important source of food and fibre for the global market, and make a significant contribution to the nation's wealth and balance of payments. In 1994, the value of Canadian agri-food exports exceeded $15 Billion, with Western Canada contributing over $9.5 billion, predominantly in wheat, barley and oilseed crops (AAFRD, 1995). According to the most recent available census statistics (Statistics Canada, 1992), there were 143,791 census farms operating in the Prairies which accounted for almost $13 billion in total farm cash receipts and over $55 billion in farm capital investments. Provincially, agriculture and agri-food industries represent a significant proportion of the Gross Domestic Product, ranging from 5.0 percent in Alberta and Manitoba to 8.0 percent in Saskatchewan. In some regions, such as southern Alberta, the agri-food sector is the most dominant economic activity.

Figure 1. Farming forces



Source: Smit et al. 1996

CLIMATE AND AGRICULTURE: THE PRAIRIE HISTORY

While there are many aspects of climate to which Prairie agriculture is vulnerable, drought can inflict the most extensive damage. Drought is defined as a long period of abnormally low rainfall, especially one that adversely affects growing or living conditions (Allaby, 1989). During this century the Canadian Prairies have experienced two periods of higher than normal temperature and abnormally low rainfall/precipitation: the 1930's and the drought of 1988. In view of expectations that droughts in a future of climate change will be worse than the drought in the 1930s (Rosenzweig and Hillel, 1993; and Karl and Koscielny, 1982), it seems expedient to review the effects that these droughts had on Prairie agriculture.

The southern Great Plains were the hardest hit by the 1930’s drought. It has been estimated that between 1933-1937, rainfall was only 60 percent of normal, devastating livestock and crop production (Phillips, 1990). Wheat yields fell 32 percent below normal and corn yields dropped as much as 50 percent. Low crop yields year after year led to the failure of about 200,000 farms and the migration of an estimated 300,000 people from the region. These disasters were a consequence of land-management practices that were associated with European techniques which came with the settlers. The practices included such things as single-wheat farming, dustmulching, mechanisation, and cultivating fallow land which exacerbated wind erosion and contributed to the dust storms that extended several kilometres into the air and carried many million tonnes of dust up to several thousands kilometres away (Lockeretz, 1978). Only after the out-migration had occurred and the climate had returned to more normal levels of precipitation, did management practices such as the adoption of conservation tillage techniques and risk management programs come into effect (Rosenzweig and Hillel, 1993).

Fifty years after the "dirty thirties" another period of severe drought occurred. The drought in 1986-1988 was more severe since the temperature was higher, as well as the precipitation deficit. Evaporation loss was also larger due to higher temperatures. As characterised by Arthur and Chorney (1992), the drought period in the 1980's was significant by its intensity, duration, area and effects. The warm and dry fall weather persisted into the winter of 1987-1988. In Alberta and Saskatchewan less than 50 percent of normal precipitation fell during the growing season. The mean temperature was 2-4°C above normal in March, April and May. The summer in 1988 was hot, dry and dusty, with mean temperatures 4-7°C above normal, and became the hottest summer on record for many localities. The combination of heat and insufficient moisture caused severe droughts in southern Manitoba, south central Saskatchewan and south eastern Alberta.

The effects on crop production and livestock was substantial across the Prairies, although Alberta faired relatively better than Saskatchewan and Manitoba (Arthur and Chorney, 1992). Production of the seven major grains was 29 percent less than in the previous year, and production of western Canada's four major specialty crops was down by 40 percent. Inventories were reduced significantly, and while marketing volumes were relatively high due to favourable prices and the depletion of older stock, export losses were estimated at $4 Billion (Phillips, 1990). One of the primary causes of the adverse effects were weeds, which became more problematic. The heat caused rapid growth and poor herbicide performance. The seeds were affected by poor germination and growing conditions (Arthur and Chorney, 1992). Despite the adverse effects on germination the crop quality actually increased in 1988, with dry conditions during the growing and harvest seasons resulting in a higher than average crop quality. The indirect effects through insects and diseases also changed. It has been found that the frequency and severity of strip rust epidemics on winter wheat in the pacific northwest varies in direct relationship to climatic variation (Wheaton and Wittrock, 1992)

Livestock production was also adversely affected through the effects on feed, from dust storms, and the lack of suitable pasture land due to drought or Prairie grass fires. In order to maintain their herds, cattle ranchers were forced to move their herds to more fertile areas where feed and pasture were more plentiful. In Manitoba cattle breeders moved their herds to northern areas, whereas in the US the drought pushed the herds south. The effects on cattle producers and grain farmers was helped out by a number of support programs. A combination of crop insurance and special drought assistance, for example, paid out over $1.3 Billion to Prairie farmers, an amount also supplemented by Provincial support programs. Despite this support, Manitoba showed net farm income losses of 50 percent and Saskatchewan 78 percent (Arthur and Chorney, 1992). Due to the effects of the drought, and previous years of low prices, an estimated 10 percent of farmers and farm workers left agriculture in 1988 (Phillips, 1990).

The adverse effects inflicted by these two droughts clearly illustrates the vulnerability of agriculture to severe climate conditions. In the 1930s, land management techniques exacerbated the effects of drought, and while farming methods had improved significantly by the 1980s, the effects from the latest drought were still substantial. Combined with estimates that future droughts under climate change could be both more frequent and severe than in previous years, the vulnerability of agriculture and its capacity to adapt demands closer examination. It may be necessary for agriculture to adopt additional measures in order to avoid (or at least minimize) the effects from future droughts.

PRAIRIE AGRICULTURE: CLIMATE CHANGE IMPACTS

To assess the impact of climate change and variability on agriculture on the prairies requires some knowledge of the possible future state of the climate. General circulation models (GCMs) are the primary source of climate change scenarios which make projections about the degree and timing of climate change. GCMs are mathematical representations of the physical laws of conservation, mass, moisture and energy to create a detailed three dimensional model of the climate system. Scenarios are built based on various assumptions of greenhouse gas concentrations, the most widely used being that of a doubling of the concentration of atmospheric carbon dioxide. Depending on the mathematical and physical formulations and the starting assumptions, the resulting scenarios will vary. The three most commonly used scenarios resulting from GCMs are Environment Canada's second generation CCC GCMII, Princeton University's Geophysical Fluid Dynamics Laboratory (GFDL) GCM, and NASA's Goddard Institute for Space Studies (GISS) GCM (Taylor, 1996).

Agroclimatic conditions

The scenarios for the prairie region all show an increase in temperature and reductions in soil moisture with a doubling of atmospheric carbon dioxide. Some models have shown an increase in precipitation while others have decreased precipitation. In either case high rates of evaporation over a longer period of time due to increases in temperature are predicted to result in diminished soil moisture. The predicted increase in temperature increases may lengthen the growing season for the prairies. An example of this is the potential reduction in the time required for spring wheat to mature by 11 days to 5 weeks depending on the location and scenario used (Brklacich, et. al., 1994). Potentially, this leads to earlier planting and earlier harvesting (McGinn et al, 1994). Opportunities for crops requiring more heating days, such as corn and sorghum, would exist for farmers on the prairies. Not only is there a potential more heating days, there is a possibility of increase in crop production in northern regions as a result of more favourable agroclimate conditions; however production is limited by soil capability.

During a typical summer, the prairies lose more water through evaporation than falls as rain making the region extremely dependent on the increased winter snowfall predicted in some models to replenish losses. Droughts could become more frequent and severe as a result. The loss of soil organic matter compounded by drier conditions will also lead to an increase in dust storms (Jones, 1996; Fosse & Changnon, 1993; & Cohen et al., 1992).

Precipitation could be the limiting factor for agriculture production on the prairies based on the current models. Not all parts of the prairies will experience the same effects, precipitation may increase in the eastern prairie and decrease in the west (Brklacich, et al, 1994). Williams, (1988), suggests that there is potential for a thirteen fold increase in the frequency of drought. With this increase in drought potential, there will be an increased demand for irrigation (Wheaton, 1994).

Crop yields

Agriculture has always been dependent on the variability of the climate for the growing season and the state of the land at the start of the growing season. The key for adaptation for crop production to climate change is the predictability of the conditions. What is required is an understanding of the effect on the changing climate on land, water and temperature.

Research on crop yields has received significant attention on a variety of scientific fronts. Plant and soil science research has provided an indication of the potential of the Canadian prairies to produce food and fibre with given conditions. In reality, it is difficult to accurately predict crop yields, because of the variability of conditions and subsequently production on the prairies. An example of this is CO_2 enrichment. Laboratory experiments have concluded the CO_2 enrichment may benefit C3 crops (e.g. rice, wheat, soybeans, potatoes and vegetables), although these improvements found in laboratory experiments may not be realised in the field.

A temperature rise extends the growing season and the farmable area, it causes earlier maturity of grain and opens up for the growing/farming of new crops. While the temperature rise is beneficial to the crops, the extra heat also affects weeds. Weeds, pests, and insects tend to get better living conditions under higher temperatures. To further increase the risks of a good crop, there is also the potential for poor herbicide performance. The combination of the weeds, pests and poor herbicide performance reduces the potential crop yields. The increase in temperature also increases evaportranspiration, which has a negative impact on crop yields.

During the growth cycle of the plant, water is needed at the initial stages of production, but not during the final stages. Low levels of precipitation has a negative effect on the germination of the seeds. Dry conditions, frequency and severity of dust storms all result in decreased production of major grains.

Given the potential changes in production variables, it is estimated that the average potential yields may fall by 10-30 percent (Williams et al., 1988). Across the prairies, crops yields will vary. All crops in Manitoba may decrease by 1 percent, Alberta wheat, barley and canola may decrease by 7 percent and Saskatchewan wheat, barley and canola may increase by 2-8 percent (Arthur, 1988). Table 1 outlines some of the changes expected in crop yields across the Canadian prairies.

Table 1. Changes in crop yields by selected scenarios

Provinces	GFDL	GFDL2	GISS	GISS2
Manitoba	increase all crops	increase all crops	decrease all crops except wheat	increase all crops
Saskatchewan	increase wheat	increase all crops	decrease all crops except wheat	increase wheat
Alberta	insignificant changes	decrease all crops except barley	insignificant changes	increase all crops

Source: Arthur, 1988.

Livestock production

The main effects of climate change on livestock from increased temperature and decreased precipitation is distress, but because livestock do not have the same limitations as crops there are potential benefits to expanding acreage.

The increasing temperatures can have varying effects, depending on when they occur. Warmer conditions in the summer can lead to stress on range and housed livestock since dry pastures, poor hay and feed production and shortages of water all lead to worse conditions for cattle. On the other hand, increased temperatures during the winter months can reduce the cold stress experienced by livestock remaining outside, as well as reduce the energy requirements to heat the facilities of those animals inside.

In the previous section, it was mentioned that crops required class 3 or better land to produce acceptable yields, however, to produce acceptable pastures does not have the same restrictions. The increased temperature would have a positive effect on the growth of the pasture, and provide better feed for livestock. This assumes that the pastures are in areas where moisture is not a critical issue.

Water resources are critical to a successful livestock operation. All livestock operations require good quality drinking water, and without it livestock will not survive. As with crops, diseases and insects could have an adverse effect on much of the livestock industry. Insects and diseases that livestock is unaccustomed to could move into the production area. Secondary effects such as dust storms and wind erosion also factor into the worsening conditions for livestock.

Livestock is more resistant to climate change than crops because of its mobility and access to feed. Livestock production could be one of the key methods for farmers to adapt to climate change through diversification of their farming mix.

Economic impacts

Agriculture is one of the oldest economic activities. This is because it is the backbone of our food supply and without it the world's population would experience food insecurity. For this reason any effect that climate change has on agriculture will be passed on to society and the economy too. Since agriculture is also dependent on the natural resource base, changing climate will require the adaptation of agricultural practices that accommodate the new climate while conserving the natural resource base.

It is difficult to predict the economic effects of climate change on the prairies. Grain sales in Manitoba could either rise or fall by several million dollars. If drought conditions similar to those in 1961 prevail, provincial agricultural output could decline by almost 20 percent, resulting in a loss of $400 million in revenue. Farm income in Saskatchewan could fall by $160-273 million, leading to declines of between $146 million and $248 million in provincial income. The value of agricultural production in Alberta could fall by 5 percent.

Diversification in the farming mixes can be a technique to reduce the losses. The changes in crop mixes and the other activities could lead to a new variety of exports. Other parts of the economy, such as agribusiness, transportation and wholesale and retail trade could increase in value and result in new jobs.

Agriculture policy

Government policies have had a significant impact on current agriculture and will continue to do so (Tyrchniewicz and Wilson, 1994). Previous agriculture policies, such as the Western Grain Transportation Act and the Canadian Wheat Board Act, rewarded expansion of cropland and made land-use changes difficult (Baydack et. al., 1996). Many policies of the past have not considered the need for adaptation, because it was not viewed as an issue.

Some of the current income protection policies such as crop insurance, and the Gross Revenue Income Program, need to be reviewed with adaptation as a guiding force. Many of these programs and policies encourage certain farming techniques and products and can have a major effect on adaptation. For example, if farmers have a guaranteed income when they use a certain practice (which may or may not be sustainable) then they will be encouraged not to use another practice which could be sustainable since it is not insurable and thus does not have a guaranteed income. As a result, many farmers make products that are insurable, using techniques that are insurable despite the sustainability, or in this case, climate change implications.

The current shifts in agriculture policy are starting to allow more flexibility in production, not only in techniques, but also in products. Agriculture and Agri-food Canada has introduced a program called the Canadian Adaptation and Rural Development Fund. The focus of this program has been to assist rural communities and farmers in adapting to changes in economic policies. While the program is not aimed at climate change, there is potential to use it to have agriculture adapt to more than just economic policies. At the moment, however, the issue of climate change is viewed only from the mitigation perspective, in terms of agriculture's capacity to reduce greenhouse gas emissions and act as a carbon sink. The issue of impacts and adaptation is grossly neglected within the debate involving climate change and sustainable agriculture (Agriculture and Agri-food Canada, 1996). Unless there is a substantial shift in the thinking of Agriculture and Agri-food Canada regarding climate change and agriculture, the economic policies designed to help facilitate adaptation to changing global economic conditions may turn out to be a missed opportunity.

Agriculture is also highly dependent on water resources. Current climate change predictions indicate that new competition for water can be expected. As well, many of the current water users will have increased demands. Given the increasing pressures on water resources, many of the irrigation and water use policies will need to be reviewed as well.

ISSUES FOR FUTURE IMPACTS AND ADAPTATION

Adverse effects from climate change can be reduced through successful adaptation, which would likely be less than the cost of the impacts that would otherwise occur without adaptations. Further, we can anticipate that there could be significant implications arising from climate change for agriculture in Canada, both directly upon our own food production, and indirectly from the impacts upon competing agricultural regions in other countries. One prediction is that there could be benefits associated with climate change, with a potential increase in agricultural production as favourable agro-climatic conditions expand northward in the Prairies. Such an expansion however would be tempered by the capacity of northern soils to sustain commercial agriculture.

Canada exports 80 percent of its wheat on an annual basis. Barley is Canada’s second largest export crop while oats and other small grain exports are confined to about 7 percent of production. Equal amount of grain corn are exported and imported to Canada across the US border and soybeans are brought in from the States. If the mix of crops changes (as is expected) because of an altered climate, the prairies’ agricultural exports are tantamount to change too. Canada will also have to import crops that formerly were produced here. This same scenario will be true for all countries. Some may become surplus producers while others will have to import more than before and others will import and export different products than before (Smit, 1989).

Table 2. Impacts of climate change on agriculture

Agriculture Characteristics	Possible Impacts	Confidence
Agroclimatic conditions	• decreased precipitation in an already spring/summer moisture deficit region • increased need for irrigation with reduced water availability • overwintering of insects and diseases which have previously been killed due to harsh climate • introduction of new insects and diseases with a warmer climate • some insecticides become less effective as temperature rises	medium
Crop yields	• yield loss in some areas • yield gain in other areas with good soil moisture • increased variability in world production due to changing climate leading to increased variability in prices and income • increased production of crops currently grown in small quantities such as winter wheat, sunflowers and corn	medium
Livestock production	• reduced winter cold stress on livestock • increased heat stress in summer • increased adequate feed supplies • increased reliance on good quality water	medium
Economic impact	• increased diversification of production • reduced economic activity due to less output and reduced crop income • other sectors could increase because of diversification • effect of fewer purchased inputs by the agricultural sector on the economy of the province	medium
Agriculture policy	• refer to Table 3	

Source: based on modified Wittrock et al., 1992

Competitive advantage in global market

A study on Canada's comparative advantage in agriculture by Smit (1989) isolates the effect of climate change from all other environmental and socio-economic conditions that could influence Canada's competitive position. How climate change could affect Canada's relative competitive advantage with its exporting competitors, as well as influencing global food imports, should also be incorporated into future research. Smit found that opportunities for producing corn and wheat would increase based on the assumption that the United States corn and wheat belts would shift into Canada given a climate warming. Opportunities for wheat and corn production would be enhanced for Russia too while they would be diminished for most other regions in the world. Climate warming would in all likelihood also lead to less favourable conditions for the production of barley, oats and soybeans. Rice production in Asia stands to gain from a warmer climate.

While information on the effects of climate change on the major crops in the world is only available for some regions, some conjecture has been made as to how they will impact upon trade. Canada can expect exports in wheat and corn to increase. Less favourable conditions for wheat production in the rest of the world except Russia mean that other potential markets exist for Canadian agriculture. This is of particular benefit to the prairies which produce the majority of Canadian wheat. The same can be said of grain corn which potentially could be exported to the US. Trade flows in grain corn may also shift from north-south to east-west with Ontario becoming a major supplier of grain corn for the prairie livestock industry. Conclusions regarding changes in Canada's competitive position in the production and trade of other crops including barley, oats, soybeans and rice remain uncertain (Smit, 1989).

Regional differences in production mix can be expected to have an effect on the prairie economies too. Arthur (1988) conducted a study of changing cropping patterns and their economic impact for Alberta, Saskatchewan and Manitoba. Using two GCMs[1] and the assumption that CO_2 concentration in the atmosphere doubles, it was concluded that the economic impacts of changing crops mixes would be limited. Crop revenues were predicted to change by between 1 and 7 percent with most results pointing toward revenue increases. Manitoba is expected to experience the least stress as a result of climate change and moisture stress with Alberta experiencing the most. Although, these effects could be mitigated by altering the cropping mix. It was found that if precipitation was to decrease Saskatchewan would suffer the greatest economic loss in terms of crop revenues. Later studies by Mooney and Arthur and Arthur and Van Kooten (in Van Kooten, 1992) have concluded that Manitoba can expect a 190 percent increase in exports as a result of climate change if soils in the north are cultivated and higher-valued crops are substituted for those being grown now[2]. In their worst case scenarios a net revenue decline was estimated at 3 percent.

Socio-economic conditions and agriculture policy

The degree to which other sectors in the prairie economies will be affected by changes in agriculture is also determined by the share of agriculture in each province's economy. In Alberta and Manitoba, for example, agriculture only comprises 5 percent of total provincial GDP and so the net effect on the total provincial economy is expected to be small (Goos, 1989). Based on the above projection that Manitoba stands to benefit from the effects of climate change on agriculture, Mooney and Arthur (1990) suggest that agribusiness, transportation and wholesale and retail trade will all increase in value and result in the addition of 17,820 new jobs to the economy. It is estimated that Saskatchewan's economy will suffer considerable loss (which has not been quantified) due to the effects of climate change on agriculture in the province (Van Kooten, 1992).

Smit (1993), for example, notes that crop insurance may distort agricultural responses to climate. Similarly, the role of the marketplace in influencing farm-level decision making may become particularly important, as agricultural policy and trade becomes increasingly deregulated.

Policy adaptations could include reforming subsidies to reflect actual risk from climate; crop assistance programs could be linked to soil conservation; rural education systems could be strengthened to encourage sustainable land use practices; taxing water by volume for irrigation purposes or encouraging water conservation laws (Chiotti, ND).

Another policy consideration that will have to be taken into account as agriculture adjusts to increased climate variability and the prospect of global warming is that of food security in the rest of the world. Canada and the United States possess roughly one-sixth of the Earth's arable land and only one-twentieth of its population. For this reason Canada and the US should not have to worry about food security at home. However, if world food surpluses diminish, Canada will be faced with increasing demand for food aid as well as the ethical question of keeping surpluses at home while many go hungry abroad or selling the

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[1] The two general circulation models used were the Geophysical Fluid Dynamics Laboratory (GFDL) and the Goddard Institute for Space Studies (GISS) models. Trigonometric distributions were also used with these models to reflect historic daily distributions of monthly mean temperatures and the scenarios were labelled as GFDL2 and GISS2.

[2] Growing conditions, soil types and the greater availability of water in Manitoba means that a wide array of cropping options exist for Manitoba that are not available to the other two prairie provinces (Arthur, 1988). Also, arable land in northern Manitoba under warmer conditions will amount to about 4.5 million hectares, whereas Saskatchewan and Alberta can expect additional land in the north to increase by 0.4 million and 1.1 million hectares respectively (Van Kooten, 1992).

food on world markets which will drive up domestic food prices (Cogan, 1992; Chiotti, ND; & Reilly, 1994).

Herbert and Burton (1995) have estimated that the cost of agricultural adaptation to current climate in Canada as over $1.3 billion, and the costs of adaptation (e.g. crop insurance, irrigation, research and development) are likely to increase under climate change (with the exception of a decrease in the cost of heating fuel). Table 3 outlines some of the potential effects from policies, and points out some of the required changes.

Table 3. Climate change and its impact on policies in agriculture

Policy	Impact of Climate Change	Confidence in Estimations	Policy Modification Required
Agricultural research	• continued need	high	need to enhance research of plant and animal varieties that are • heat and stress resistant • resistant to new insects and diseases
Water policy	• water availability for irrigation	medium	• irrigation policy change based on water availability forecasts • increased research to develop drought tolerant crops
Farm numbers	• increased difficulty for farmers to survive increasingly adverse conditions • increased exodus of farmers from the land • continued rural depopulation • increased reliance on program payments	high	assist the restructuring of agriculture • transition programs for those who wish to exit • restructuring of financial instruments • design market neutral programs
Soil conservation	• reduced organic material • increased incidence of soil erosion	high	• increased emphasis on soil conserving practices • continuation of the Canada-Saskatchewan Soil Conservation Program • restructure agriculture programs so as not to promote breaking of marginal land
Diversification	• continued need	medium	• continued emphasis on diversification
Trade	• decreased contribution to	low	• diversify provincial economy

Policy	Impact of Climate Change	Confidence in Estimations	Policy Modification Required
	provincial GDP as agriculture output decreases		
Financial and management support	• increased reliance on program payments as climate change worsens the farm situation	low	• assist restructuring of agriculture • develop market neutral programs
Inspection	• new types of livestock pests and diseases will be introduced with a milder climate • new types of crop disease and pests	low	• education of inspection and grading officers to identify potential problems • new legislation and/or regulation for crop standards and grades

Source: Miketinac in Wheaton and Wittrock, 1992

Agriculture and sustainability

In terms of the effect of changing crop mixes and revenues on the rest of the prairie economies, other sectors will be affected by expenditures for farm inputs and consumer goods and services. Discretionary expenditures change in direct response to changes in cash flow, hence those scenarios that produce a negative effect on prairie agriculture will pass on those negative effects to other sectors too but to a lesser degree (Arthur, 1988). While it is tempting to compare results from different sources, this should be done with caution since these studies have all been done using different assumptions and methodologies. Furthermore, most studies only take the effect of climate change into account while all other factors are held constant. Given the complexity of combining climate change models with economic and other models and the degree of uncertainty inherent in all of these models, figures and predictions that are presented as economic impacts in section III have to be interpreted accordingly.

While past experience has indicated that the agricultural sector is able to respond and adapt quickly to changes in climate, government will play a role in how the sector adapts and how quickly. Government compensation, subsidy and assistance are programs which the government uses to offer rural communities some form of economic and social security. However, if farmers on an individual level are always able to access government assistance when faced with climatic catastrophe they do not have an incentive to change their practices so that they match the climatic reality since the government will always bail them out. A balance needs to be found between government programs that help in emergencies and act as short term coping strategies versus government programs that encourage their use as an adaptive strategy (Smit, 1995; & Van Kooten, 1992).

The changing climate on the Canadian prairies could have a significant role to play on the population. Assuming that agriculture moves to more diversity, there will be an increase in available jobs. This is based on the fact that cereal production on the prairies is very mechanized, while other production, such as livestock and specialty crops are more dependent on labor. The counter argument is that if climate change has reduced the ability of the prairies to support humans, based on the quality and the quantity of resources such as water, soil, flora and fauna, then out-migration can be expected.

While temperature conditions may be favorable for growing new types of crops in the prairies, moisture deficits may preclude these new crops as an adaptation option. However, in order to adopt these new crops moisture deficits could be overcome through the use of irrigation (also an adaptive strategy). Decreasing availability of water for all users on the prairies will lead to conflicts as producers compete with recreationists, household users, electrical utilities, and the manufacturing and other industry for water for irrigation (Rosenberg, 1992; & Wittrock and Wheaton, 1992).

RECOMMENDATIONS

It may be possible to extract additional information from previously conducted studies to address these knowledge gaps, but it is likely that new research will need to be undertaken.

- A vulnerability analysis should be done for all three prairie provinces of the effect of climate change on agriculture and the second round effects on the other sectors of the economy. An attempt should be made to quantify the costs and benefits.
- General equilibrium models should be integrated with climate change and agricultural models in order to try and take the dynamic nature of things into account.
- Further research is needed on farm-level decision making, examining the role of climate change variables vis-a-vis societal and other forces in influencing land management adaptations.
- Although some models predict a northward movement of agriculture, further research is needed to determine the suitability of these soils to a shift in agriculture.
- Based on expectations of what climate variability and change can be expected on the prairies and how it will affect agriculture, policy needs to be analysed and adjusted so that it acts as an incentive to farmers to adopt the appropriate management strategies and agricultural practices for the new climate reality.
- Further research is needed to determine the indirect effects of climate change; specifically the impacts on agriculture elsewhere and the effect upon Canada's competitive position in the global marketplace.

The following research questions should also be considered in future research on climate change and variability impacts on Prairie agriculture:

1. What are the attributes of climate to which agricultural systems respond?
2. Why do responses differ, and what characteristics of farming make certain types of regions more vulnerable or adaptive than others?
3. What non-climatic conditions influence the propensity to adapt?
4. What role do crop insurance, subsidies and technological development play in influencing adaptations in farming systems?
5. What are the constraints on and incentives for adaptation in the future?
6. How sustainable are land management responses to climate change?
7. How can agriculture become more sustainable to climate change?

source: Smit et al. (1996) and Chiotti et al. (1997)

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APPENDIX B

FOREST ECOSYSTEM AND CLIMATE

FOREST ECOSYSTEM AND CLIMATE

E. Wheaton
Climatology Section, Environment Branch
Resources and Environment Group
Saskatchewan Research Council
Saskatoon, Saskatchewan

"*In the boreal zone of central Canada, both natural and managed forest ecosystems appear particularly sensitive to global change, with potentially serious consequences both regionally (in vegetation composition and distribution) and globally (as feedbacks to the global climate)*." (Price and Apps 1995:212)

SUMMARY

Unmitigated global warming is estimated to have significant effects on the Western Canadian boreal forest. The boreal forest is a mainstay of the Canadian economy, has social, environmental and intrinsic importance. The western boreal forest is particularly sensitive to direct effects of climatic changes such as drought and indirect effects such as fire and insect disturbances. The boreal forest is the ecosystem that is expected to be affected the most by future climatic changes because of its high latitude location and because of its climatic sensitivities.

Key climatic factors driving current and future forest ecosystem changes appear to be the rate of change and extremes, especially drought. Drought events are significant through their effects on soil water availability, fire, insects and diseases, and the carbon budget. Estimated impacts are possible future scenarios, not forecasts and are summarised:

- growth and productivity could improve in central and northern regions, especially on favourable sites, and decrease in the south, especially with increased droughts.
- climate zones will shift northward, putting stress on the forest ecosystem with rapid changes.
- disturbances (e.g., fire, insects, and diseases) could increase, especially with already stressed ecosystems.
- increasing frequency and intensity of drought could result in decline and dieback as well as increasing stress from other disturbances such as fire and insects.
- demand for new tree species for regeneration could increase.
- the region fluctuates between being a net source and a net sink of carbon depending mainly on natural disturbances such as fire and insects, and forest management practices.
- net loss in the total area of the western Canadian boreal forest is expected.
- changes in land use potential would affect multiple use of forest lands (e.g., biodiversity, increasing agriculture, recreational and other non-timber uses).
- increased productivity could benefit Canadian consumers and result in losses for producers.

Research formulation and implementation, impact assessment, and adaptive strategy development regarding climatic change and variability appear to be in their early stages. Many key policy and research questions remain priorities. The western Canadian boreal forest is a key area for further work because of the combination of the large climatic changes expected, the greater role of disturbances, and its role as a potential carbon source or sink.

INTRODUCTION AND OBJECTIVES

The Western Canadian boreal forest

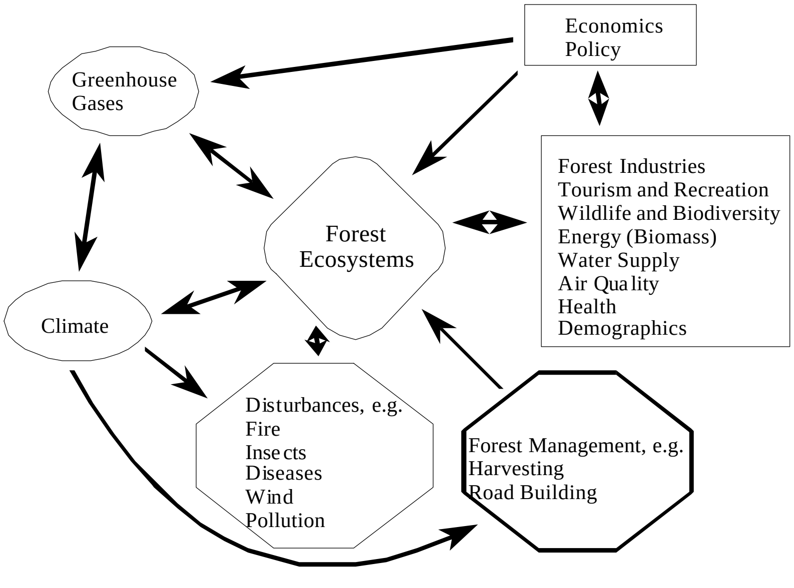
"Forests sustain the economies of hundreds of communities across the country, moderate our climate, prevent soil erosion, improve air and water quality, and provide habitat for countless species of plants and animals. They also offer a multitude of recreational opportunities that are enjoyed by Canadians and visitors from abroad." (Canadian Forest Service (CFS) 1996*a*:6).

The study area, the western Canadian boreal forest, is a portion of a massive circumpolar northern forest region slicing across the Northern Hemisphere. The boreal forest has a wide range of known and unknown values and uses, besides intrinsic values. The Canadian boreal forest is very important to the society, economy and environment, in ways that are often obvious, but also sometimes less tangible. About 45 percent of Canada's landbase is covered by forest, providing about $19.3 billion in exports, and direct plus indirect employment for 880,000 people in 1994 (CFS 1996*a*:92 and 1996*b*:162).

These non-market values may be greater than all other commercial values (van Kooten in Wheaton et al. 1987). The forest provides wildlife habitat and water resources. It improves air quality and contributes to climatic control and soil conservation. Humans use the forest for recreation and enjoy its beauty. Our economic growth, prosperity and quality of life can be maintained only through sustainable development and prudent management of the forest resources faced with current and future climatic changes (Singh and Wheaton 1991).

The interactions, direct and two way, of the greenhouse gas-, climate-, forest ecosystems-, human activities-, policy-, greenhouse gas system are generalised in Figure 1. Climate is a key factor in the location and growth of forests. Forests, in turn, provide a base for several sectors including the forestry, tourism, and fisheries. These sectors affect the economy and society, whose changes can in turn can influence policy. Policy is a key way to bring about changes in greenhouse gas emissions which are a main factor in climate change. This system has several two-way interactions. For example, although climate affects the forest, changes in the forest can affect the regional and perhaps the global climate. Industrial activities, such as harvesting, affect the forest ecosystem and are in turn determined by the type of forest.

Figure 1. Generalised model of climatic interactions important to the forest ecosystem.



Objectives and scope

This chapter reviews recent and available literature emphasising climate and the western Canadian boreal forest. The focus is on literature after about 1991 because Wheaton (1992) provides an extensive review of work previous to that time. That review also included results from interviews with forest experts.

This chapter is limited to an overview of a selected number of issues. Other issues, such as biodiversity, soil processes, carbon fertilisation, and integrated assessments were beyond the scope of this chapter, but should be addressed. [“Carbon fertilisation” refers to the effect of increasing carbon dioxide which provides potential increasing plant productivity (e.g. Lemon 1983). “Biodiversity” refers to the variety of living forms and their abundance; it is a characteristic of biological systems at all organisational levels (Noss 1990)]. For further information on these topics in the context of a changing climate, refer to Wheaton (1993, 1996) and Wheaton et al. (1992).

The objectives of this chapter are to provide an overview of implications of climate change for the study area. They are framed by the following questions (Herrington 1997 p. comm.). The list is comprehensive and the reader is warned that the literature is too sparse now to adequately address some of the questions, especially numbers three and four.

1. What do we know about the connection between current climate variability, including extremes, and the boreal forest? How sensitive is the boreal forest ecosystem to climate? These questions are addressed in the *sensitivity and impacts section*.
2. What changes may occur in the boreal forest if global warming continues over the next 50 to 80 years? Why might climate change be a problem for the boreal forest ecosystem? What are the possible impacts of global warming for characteristics such as regional climate zonation, disturbances, growth, and economics (for 2050-2080 AD)? These questions are considered in the *impacts section*.
3. How will these changes affect society, the economy, and other aspects of the environment? Implications for and interactions with other sectors are discussed. These sectors or activities include tourism and recreation, energy (biomass, carbon budget), agriculture, communities (e.g., aboriginal people). The impacts of a changing climate are usually considered in isolation from other trends affecting the forest. Other impacts result from changes in land use, forest management (e.g., harvesting), multiple use demands, and pollution, for example. A changing climate would exacerbate or perhaps alleviate the effects of these other changes. These questions are addressed in the *economics section*.
4. Will other effects, for example, population growth or forest over-harvesting, overwhelm any climate change impacts on the forest or people? Will climatic change exacerbate these other effects?
5. What should be done? While more plausible climatic change scenarios are needed at the regional level, more research is certainly needed on climate change impacts. What should the priorities be? Should we focus on reducing greenhouse gas emissions? Should we develop and begin implementing adaptation measures? What adaptation measures are most appropriate? Specific recommendations are embedded in the text so that they are close to their rationale, but general recommendations are in the last section.

Future climatic changes expected

The science of climatic change has progressed considerably since the initial Intergovernmental Panel on Climate Change assessment (IPCC 1990). Global warming and other climatic changes are forecast to continue into the future. The annual to decadal changes would include considerable variation, but the average rate of warming would likely be greater than any seen in the last 10,000 years. Temperatures are projected to continue to increase beyond 2100, even if concentrations of greenhouse gases were to be stabilised by that time (IPCC WG I 1996).

Confidence in estimations of future possible climates at the regional scale remains much lower than at the global or continental scale. As well, estimates for temperature have higher confidence than estimates for other impacts such as precipitation and soil moisture. However, large changes in the frequency of extreme events are known to occur with small changes in mean values of climatic elements. Models agree on the following changes of future climate for mid-latitude Northern Hemisphere land areas (IPCC WG I 1996):

- night-time air temperatures rise faster than day-time temperatures.
- soil moisture increases in winter and decreases in summer.
- precipitation increases in winter.
- snow cover area and duration decreases.
- ground temperature increases

While our knowledge of the physical changes that could occur on the Prairies as a result of the expected climatic change is still speculative, in part because of the scientific uncertainties and in part because of the difficulties of relating these changes to the regional level, it is important to understand the impacts of "probable" changes. Probable change refers to the likely regional outcome according to the IPCC projections of change, that would occur in a mid- to high-latitude region with a continental climate.

Relatively large changes in the future climate of interior western Canada are possible as a result of greenhouse-gas-induced climatic change. The outcome of the temperature change would be a longer frost-free period, more evaporation in the summer, and fewer or shorter cold spells in the winter. Changing precipitation patterns are also likely to occur; these are less predictable, but are likely to result in lower summer rainfall, even if total rainfall remains the same or increases.

Significant mean temperature changes of about 0.9 to 1.7°C are already evident in the climatic record for this region in the past century (Gullet and Skinner 1992, Singh and Powell 1986). More recently, the 1980s was the hottest decade in this region as well as globally (Phillips 1993). Regional warming may have already begun to affect this portion of the boreal forest.

Drought is currently a constraint on forest growth and a disturbance accelerator in this region. Future droughts are expected to become more intense and frequent (e.g., Williams et al*.* 1988). There is concern that the projected increases in precipitation may not be of adequate amounts or proper timing to offset the increases in evapotranspiration demand. The projected decreases in precipitation in some months would intensify drought.

Temperature and precipitation maps of expected climatic changes for the Prairie Provinces from the Canadian Climate Centre's second generation GCM run are in Wittrock (1992). For descriptions of sets of possible changes, including a historical drought analogue, refer to Wheaton et al*.* (1992).

SENSITIVITY OF THE FOREST ECOSYSTEM AND IMPACTS OF CLIMATIC CHANGE AND VARIABILITY

"Forests are highly sensitive to climate change... Sustained increases of as little as 1°C in mean annual air temperature can be sufficient to cause changes in the growth and regeneration capacity of many tree species. In several regions, this can significantly alter the function and composition of forests; in others, it can cause forest cover to disappear completely (Medium Confidence)." (IPCC WG II 1996:97)

This section reviews the sensitivity of the boreal forest sensitivity to climate and the estimates of climatic change with emphasis on the western Canadian boreal forest. What impacts are estimated for the last half of the 21 century? How sensitive is the western boreal forest to climate change and variability? Many aspects of the boreal forest are either directly or indirectly related to climate. Flowering, pollination, seed formation, germination, and competitive success of seedlings are particularly climate sensitive. Other sensitivities include soil nutrient status, hydrology, community dynamics as well as structure and function (Singh and Wheaton 1991).

The circumpolar boreal forest is often considered to be predominantly temperature limited. The western interior Canadian forest, however, is thought to be temperature limited at its northern edge and moisture limited at its southern boundary (e.g., Singh and Wheaton 1990, Hogg 1994). It also has a greater fire hazard than the eastern Canadian boreal forest. Risk factors such as fire, wind, drought, insects and disease play key roles in the health and growth of the boreal ecosystem (e.g. Wheaton et al*.* 1987).

One of the first studies to estimate the ecological and economic impacts of future possible climatic changes in this region was by Wheaton et al*.* (1987; update by Wheaton et al*.* 1992). Although preliminary, this study was a comprehensive assessment of impacts on characteristics including disturbances, zonation, growth and yield, biodiversity, and forest economics (Table 1). The work was done by a combination of scientists from the federal and provincial governments, universities and the private sector. It was funded and directed by the Canadian Climate Centre. Zoltai (1988), Rizzo (1988), and Sargent (1988) also compared current and future possible positions of the vegetation zonation.

Several others have written about climatic change impacts to date, but most of the work appears to be at an early stage. An updated version of Table 1 highlights more recent climatic impact results (Table 2). This section updates findings in these categories and others. It covers the categories of droughts, growth, productivity and regeneration, zonation, area, disturbances, carbon budget, and economics.

Droughts-climate lessons from the past

Past extended droughts and changing climates in the boreal forest may provide a preview of the effects of continued global warming, as well as a means of sensitivity analysis. Twenty years of biophysical records for the Experimental Lakes Area of northwestern Ontario indicated many changes that may be comparable to those expected in the future (Schindler et al*.* 1990). Their study area is outside the one considered here, but close enough to warrant attention. They report that the period of record has been one of mostly continuous warming and increasing frequency of drought. The rising air and lake temperatures and lengthened ice-free season also caused evapotranspiration to increase and runoff to decrease. Large areas of forest cover were lost to fire and were associated with an observed increase in wind speed. Several ecological trends were also measured. Populations and diversity of phytoplankton increased in one lake, but primary biomass production showed no evident trend. Summer habitats for cold stenothermic organisms such as lake trout and opossum shrimp decreased.

The droughts of the 1980s, especially 1988, were among the most severe droughts in North America in the past one hundred years. These droughts also extended northward to affect the study area (Wheaton and Arthur 1989). Forest effects included lower than normal annual wood volume increments (estimates), higher than normal seedling mortalities, tent caterpillar and spruce budworm outbreaks and considerable fire damage and fire suppression costs (Wheaton et al*.* 1992*b*). Tree ring analyses indicate that radial growth of aspen is reduced by at least 90 percent during a severe drought (Hogg and Hurdle 1995). In contrast, Botkin and Nisbet's (1992) simulation results (including boreal species) suggest that a cold or warm decade does not significantly affect a forest, but a cold or warm century does act as an environmental bottleneck and affect forest composition.

Even a warming of 1°C could cause the boreal forest to move northward (Horgan 1989, IPCC WG II 1996). This sensitivity is made apparent by examining the time series graphs of mean annual temperature of the boreal forest subregions in (Singh and Powell 1986). The forest-grassland transition and the predominately forest subregion in western Canada are only separated by only about 2°C in mean annual temperature. The effect of a 2°C increase is mainly manifested through increased evaporative demand, reduced soil moisture, and therefore more severe drought. This results in reduced stomatal conductance, reduced growth, and more severe dieback events, especially when combined with other stresses (Hogg p. comm. 1997). A persistent increase even that small could result in a pronounced mismatch of climate and ecosystem (Wheaton and Thorpe 1989).

Table 1: General estimates of, confidence in, and uncertainties of impacts of climatic warming (2 x CO_2 scenarios) on forest ecosystems in Saskatchewan (Wheaton 1992)**.**

Forest Ecosystem	Possible Impacts	Confidence in Estimate[1]	Uncertainties	Sources
Growth and Productivity	• Decrease in south, increase in central and north. • CO_2 enrichment effects?	Medium to Low Low	• Effects of extremes, especially temperature and droughts. • Effects of climatic changes on roots. • Growth - climate relationships	Wheaton et al. 1987
CO_2 Enrichment and Storage	• Increase in growth and water use efficiency.	Medium to Low	• Effects on mature trees, acclimatisation, effects of other limiting environmental factors.	Wheaton et al. 1987
Ecoclimatic Zonation	• Northward shift by hundreds of kilometres.	Medium	• Migration rates, effects of depletion factors, such as fire; Adaptation capabilities; Ecosystem response lag.	Rizzo 1988 Sargent 1988 Wheaton et al. 1987
Area	• Decrease.	Medium	• As above.	Rizzo 1988 Sargent 1988 Wheaton et al. 1987
Competition	• Stronger ground vegetation competition	Medium to Low	• As above, effect of site factors.	Wheaton et al. 1987
Fires	• Increase, especially in the south	Medium	• Effects of weather extremes; • Change in patterns of storm belts; • Change in fuel complexes; • Change in fire management.	Wheaton et al. 1987
Insects	• Increase, especially for some types • Movement of insects from the south	Medium to Low Medium to Low	• Relations of climate and weather with insect dynamics.	Wheaton et al. 1987
Diseases	• Increases, especially for some types • Movement of diseases from the south	Medium to Low	• Relations of climate and weather with disease dynamics.	Wheaton et al. 1987
Soil processes	• Decomposition rate increase, acceleration of nutrient cycling • Permafrost active layer increase • Permafrost zone shifts northward	Medium Medium Medium	• Relations of climate variations with soils. • As above. • As above.	Harris et al. 1975 Wheaton et al. 1987

[1] *estimated by Wheaton*

Table 2: Forest changes possible with future climatic change in the western Canadian boreal Forest - Some results from other studies [Refer to Table 1 (Wheaton et al. 1992) for studies previous to about 1991].

Characteristics	Impacts	Climate Scenarios	Impact Model	Uncertainties/ recommendations-examples	Source	Comments
Growth, productivity, competition, regeneration	Biomass change of more than –50%, +10 percent, +30 percent and +40%	GFDL, UKMO, GISS, and OSU	FORSKA2	Effects of climatic variability, including droughts. Climate-response relationships.	Price and Apps 1996	Results varied significantly with different climatic scenarios.
	Reduced productivity and increased mortality in a large part of the south.	CCC GCMII90 (4-5°C increase in mean temperature and 11% increase in precipitation).	Moisture index	As above. Disturbances are likely to exacerbate the impacts.	Hogg and Hurdle 1995	
	Biomass increases in general. Seasonal changes are summer decreases and spring and fall increases.	CCC GCMII (1990)	Climatic index of biomass potential	Other climatic scenarios should be used.	Wheaton and Wittrock 1993	
	Conifer dieback and replacement by grasses.	GISS 1988 and GFDL 1987	Canadian Climate Vegetation Model (CCVM)		Lenihan and Neilson 1995	Changes are drought induced.
Zonation and area	Aspen parkland climate would replace much of the south and west portions.	CCC GCMII 1990	Climatic moisture index	As above.	Hogg and Hurdle 1995	
	No pronounced northward shift of vegetation zones. Species invasion of types not currently found are indicated.	GFDL, UKMO, GISS and OSU	FORSKA2	See above at Price and Apps 1996.	Price and Apps 1996	
	Northward shift of boreal and grass prairie formations, especially with GFDL.	GISS 1988 and GFDL 1987	Canadian Climate Vegetation Model (CCVM)	Transient response of vegetation.	Lenihan and Neilson 1995	

Table 2: Continued

Characteristics	Impacts	Climate Scenarios	Impact Model	Uncertainties/ recommendations-examples	Source	Comments
Fire	Doubling of risk and area burned in southern parts; decreases towards northeast and southwest Albertan boreal.	CCC GCMII 1990	FWI System	Drought, synoptics, species changes, season length.	Bergeron and Flannigan 1995	Average risk decreases over Eastern Canada.
	Fire season lengthens by about 16%.	CCC GCMII 1990	Canadian Forest Fire Danger Rating System - variation	Frequency of rainfall events and drought.	Wotton and Flannigan 1993	
	A 46%increase in annual area burned.	GFDL 1980, GISS 1988, OSU 1989	Seasonal Severity Rating of the FWI.	Relation between area burned and seasonal severity rating.	Flannigan and Van Wagner 1991	
Carbon Budget	Net source of 1.4 Pg C to a net sink of 9.2 Pg C depending on management.	Management policies are drivers: controlling natural disturbances, increasing regeneration rates, converting non-stocked land to stocked forests. No climate change assumed.	Carbon Budget Model of the Canadian Forest Sector	Climate change, especially effects on disturbances, management implementation.	Price and Apps 1995	Importance of disturbance regimes were emphasised.

Global boreal forest changes

“Because warming is expected to be particularly large at high latitudes, and boreal forests are more strongly affected by temperature than forests in other latitudinal zones, climate change is likely to have its greatest impact on boreal forests (High Confidence).” (IPCC WG II 1996:98)

Working Group II of the IPCC (1996) reviewed the state of world knowledge regarding climatic change impacts on physical and ecological systems. The major findings from this reference for the global forest ecosystems are summarised in Table 3 with special reference to the boreal forest. The impact estimations are made for some time after about 2050 AD. There is a general consensus that, because of its high latitude location and sensitivity to temperature, the boreal forest is likely to be the forest type most affected by climatic change.

Table 3: Forest changes expected with future global warming (about 2050) onward - a summary of findings from IPCC WG II (1996) with reference to the boreal forest

Characteristics	Impact Estimates	Confidence	Comments
Growth	Changes in growth capacity of many tree species are expected.	Medium	Changes can be caused by sustained increases of 1°C (mean annual temperature). Temperature niches for growth and reproduction are narrow for many species.
	Net primary productivity may increase, but standing biomass may not increase, depending on the disturbances, especially droughts.	Medium	
	Disturbances will likely decrease the average age and biomass with greatest impacts on the southern areas of the boreal forest.	Medium	
Regeneration	Changes in regeneration capacity of many tree species are expected.	Medium	As above.
Zonation	Boreal forests are expected to be most affected (e.g. species shifts and decreases in area).	High	Because the greatest warming is expected for high latitudes, and boreal forests are more sensitive to temperature than other forests. Forest distribution is generally limited by climate (water availability and temperature).
	Suitable ecoclimates could shift more quickly than many species can naturally migrate. new major vegetation types are expected. Slow growing and slow migrating species would be replaced by more adaptable species.	High	
	Structure and function would be altered and forest cover may disappear.	Medium	
	Northern trellises will probably advance slowly into areas that are currently tundra.	High	
	The southern limit of the boreal forest will likely be replaced by grasslands or temperate pioneer species.	Medium	

Table 3: Continued

Characteristics	Impact Estimates	Confidence	Comments
Disturbances	More frequent outbreaks and extended ranges of pest and pathogens are expected.	Medium	
	Increasing frequency and intensity of fires are expected.	Medium	
	Rapid forest decline is expected if conditions move toward drought or flood extremes. Any changes in water availability are likely to greatly affect species distribution.	High	Forests are particularly vulnerable to extremes of water availability. Most GCMs indicate significant declines in growing season net soil moisture in continental areas.
Carbon Budget	Forest changes in response to changing climates may release large amounts of carbon transiently.	Medium	Because the maximum rate of carbon loss is greater than the rate of gain.
	Disturbances will likely decrease the carbon store, with greatest impact on the southern limits of the boreal forest.	Medium	
	Net carbon losses may occur in the boreal forest.	Medium	Because of the increase in soil organic matter decomposition, for example.
Biodiversity	Significant species losses are anticipated due to climate change and habitat degradation. Transient enhancements are possible because forests might form a richer mosaic of patches.	Not specified	Climatic change effects on biodiversity are still poorly understood. However, it should be considered one of the most important impacts because of its permanence.

Warning: Future responses are estimations, not precise forecasts.

Climatic impacts on growth and productivity, regeneration, zonation, disturbances, carbon budget and biodiversity are summarised and labelled with confidence levels. Levels of confidence were subjectively assigned to major findings by the IPCC WG II (1996). A high confidence denotes wide agreement based on many findings, through several lines of investigation. A medium confidence level indicates agreement, but not enough to rule out alternative hypotheses. The low confidence category is used for cases of considerable uncertainty about a conclusion. The uncertainty could stem from lack of information or agreement, for example.

In general, the circumpolar boreal forest is likely to decrease in area, biomass, and carbon stock, with a move toward younger age-classes and considerable disruption at its southern boundary. Carbon dioxide enrichment is estimated to have less effect than in warmer climates.

Growth, productivity, regeneration, migration zonation, and area

"Climate change is expected to occur at a rapid rate relative to the speed at which forest species grow, reproduce and establish themselves." (IPCC WGII 1996:5)

The structure and function of the boreal forest ecosystem are more clearly dependent on climate than many other ecosystems (Wheaton et al*.* 1987). For example, net primary productivity rises with both temperature and precipitation. Trees growing under different climatic regimes have different growth rates and productivity. Climate has considerable influence on growth and disturbance factors.

Have effects already occurred related to the past significant warming? Future warming over the next century is expected to be greater in rate and magnitude. We need to ask how much more change can this boreal forest ecosystem endure before significant effects occur.

Monitoring for present growth and other characteristics is in progress and is beginning to address these above questions. For example, Halliwell et al. (1996) have surveyed forest site characteristics in a transect across the central boreal forest as a contribution to the Boreal Ecosystem Atmosphere Study (BOREAS). The 97 sites extended from aspen parkland to sub-arctic woodland. Such monitoring provides essential baseline data for assessment of the sensitivities of the boreal forest to global change. The southern sites (Prince Albert, Saskatchewan) tended to have greater values for basal area, volume, and biomass than the northern sites (Thompson, Manitoba).

Growth in the study area's forest is limited by both temperature and water availability. Productivity impacts are largely dependent on the response of individual species. Where moisture supplies and other factors are not limiting, increased temperatures could bring higher growth rates. Alternatively, droughts constrain growth and productivity (Singh and Wheaton 1991).

Rising temperatures tend to stimulate the development and seed germination of many species. This would enable the northward shift of forest cover if not constrained by soil type, for example. A longer growing season would tend to increase growth and productivity. The strength of the positive growth response to increasing temperatures will depend on water and nutrient availability, and the frequency of fires (IPCC WG II 1996).

The modelling of growth, productivity, and zonation response is one of the favoured routes to estimating future climatic effects on the forest. Various models have been used and they show large shifts in species composition and in the present boreal vegetation zonation. IPCC WG II (1996) findings indicate that net primary productivity is likely to increase in response to warming, where it is not constrained by drought. Results from recent modelling work are summarised in Table 2.

Botkin and Nisbet (1992) used a forest growth model to study forest responses to long-term climatic change. Their projections suggest rapid and dramatic response of mid-latitude forests to a climatic change transient scenario developed by the Goddard Institute for Space Studies [GISS]. The results strengthen the argument for careful planning now for the contingency of major disruptions in forests with global warming.

The present geographic distribution of vegetation zones is largely affected by climate at a global scale and at scales such as the boreal forest (e.g., Holdridge 1964, Tukhanen 1984). At present, the southern boundary of the western Canadian boreal forest meets the aspen parkland zone. This zone is characterised by grassland with patches of trembling aspen (*Populus tremuloides* Michx.). The northern boundary of the forest is a transition to a tundra zone.

Various analyses of the climatic controls of and interactions with the vegetation zonation of the study area have been done and are important to the question of the effect of shifting climatic zones. Although temperature affects the distribution of the boreal vegetation, moisture availability is likely more important in drier regions, such as the boreal forest of western Canada (e.g., Hogg 1994, Wheaton and Thorpe 1989).

Hogg (1994 and 1996) showed that the southern limit of the western boreal forest corresponds most closely with climatic moisture regimes (annual precipitation minus potential evapotranspiration [P-PET]). Thermal characteristics of climate (e.g., growing degree-days) showed an inconsistent relationship with the southern limit (Hogg 1994). This close relationship for the southern boundary suggests that it is likely governed, directly or indirectly, by climatic moisture deficiency and drought occurrence. One of the most likely explanations of this control is that conifer regeneration from seed is restricted in drier climates. Even in naturally forested regions, moisture deficiency was found to frequently reduce the germination rate, photosynthesis, and survival of conifer seedlings. Coniferous forests and peatland development are generally limited to areas where annual precipitation is greater than potential evapotranspiration.

Climatic zones are expected to shift pole-ward by several hundreds of kilometres (300 to 500 km) over the next century. The boreal forest's response to this shift is not clear, but the IPCC WG II (1996) has high confidence that the northern tree-lines are likely to advance slowly into regions that are currently tundra. Existing populations of trees near tree lines could have positive growth responses. Vegetation zonation shifts could have considerable socioeconomic and environmental implications, depending on the rapidity of the changes and the affected sectors' awareness and adaptability.

Effects of past long-term climatic changes lend credibility to these estimates of ecoclimatic shifts. Warmer and drier conditions in North America peaked about 6,000 years ago. As a result, the northern limit of the boreal forest extended far north of its present boundaries, and grasslands occupied most of the southern portions of the boreal region in western Canada (Ritchie and Hare 1971). During this period, peatlands were absent over much of the present southern portion of the western Canadian boreal forest (Zoltai and Vitt 1990). There is good evidence of expansion and recession of the boreal forest in both North America and Eurasia in response to temperature changes over the past 10,000 years. The anticipated temperatures for the next century exceed any changes over the past 10,000 years (IPCC WG I 1996). Therefore, changes in the geographical location of the boreal forest are expected to also exceed past changes.

Southern parts of the boreal forest may be replaced by grassland or other vegetation, or by agriculture where soils are suitable. Species shifts may occur in the mid-boreal regions. Large portions of the forest will be mismatched with their climatic zone (IPCC WG II 1996). For example, much of the current boreal forest in western Canada would have a prairie-like climate (Rizzo and Wiken 1992, Lenihan and Neilson 1995). On the southern edges of the forest, reduced winter chilling may disrupt both vegetative growth and reproductive processes. Unfortunately, it is not yet possible to predict transient forest responses at a regional to local level (IPCC WG II 1996).

Large or prolonged temperature increases will also lead to a shift from coniferous to deciduous tree species. This may have a positive feedback on productivity through increased nutrient cycling (IPCC WG II 1996).

Forests will be forced to migrate to keep up with the shifting climatic zones. The natural migration rates of forest ecosystem species may be too slow to keep up with the rate of climatic change. Some researchers speculate that this could cause transitory forest decline, especially with soil or daylength constraints. Other researchers suggest that change will be buffered by the adaptability of invading species. Fire and other disturbances will become an increasing factor in effecting zonation changes (IPCC WG II 1996).

Each species is affected differently and will migrate differently. Each species has different tolerances, genetic variances, and dispersal rates, so each will differ in its adjustment to the changing environment. Therefore ecosystems will not migrate as a unit in response to shifting climatic zones. The results could be new assemblages and new ecosystems (e.g., Singh and Wheaton 1991). Some species may be able to persist in the current location for some time, until certain survival thresholds are reached or disturbances occur, but others are expected to die out (Morecroft et al*.* 1997).

The success or failure of migration depends on many interacting factors, one of the most important being the rate of climatic change. A rapid rate of climatic change beyond the immediate adaptive range of many boreal tree species will result in increased failures in regeneration and restocking efforts in harvested areas. The global warming will reduce natural regeneration of present commercial tree species, particularly in delicately balanced southern geological transition zones (Singh and Wheaton 1991).

What changes in boreal forest area are likely with climatic induced migrations? The northward expansion of mature boreal forest would tend to be slower than the loss of southern forest area to grassland and other types. Also, the squeeze into the tundra is limited. For example, Rowe and Rizzo (1990) write that, on the northern edge, the subarctic lichen woodland may also be severely affected by a changing climate. The warmer temperatures might improve the climate for the woodland, but may not compensate for the inability of the acid till soils to support a closed-crown forest. The rate of migration may not be rapid enough to keep pace with the climate and the soils may be an infertile barrier to the forest's northward movement. The summer drought with more frequent fires and insect invasions and shifting permafrost could change the subarctic black spruce woodland into predominantly jack pine. So the grasslands may squeeze the boreal forest from the south and the northward barriers may decrease the total area of the forest (Rowe and Rizzo 1990). Other work also suggests that the area of the boreal forest is expected to decrease (e.g., Singh and Wheaton 1991, Rizzo and Wiken 1992, Sargent 1988).

How drought tolerant are boreal species? This question has implications for changes in the southern parts of the zone. Aspen occurs naturally in drier areas than conifer species. However, high mortality of aspen groves has occurred during past prairie droughts of 1961 (Zoltai et al. 1991 in Hogg 1994) and of the 1980s. Also, mature planted conifers in the aspen parkland seem to have suffered less during recent droughts (Hogg p. obs. in Hogg 1994). The more southerly distribution of aspen is likely a result of its vegetative mode of regeneration. The drought tolerance of different species, in terms of regeneration and growth, for example are important questions that require further attention, even with the present climatic probability of droughts.

Hogg and Schwarz (accepted) examined the influence of dry climates on white spruce (*Picea glauca* [Moench] Voss) regeneration. They concluded that the current aspen parkland and grassland climates are too dry to allow natural regeneration of white spruce and other conifers. If continued global warming brings drier climates to the boreal forest, conifer regeneration may be significantly reduced.

The climatic control of the southern limit of the boreal forest indicates that even a slight shift toward drier climatic conditions could have a significant impact on natural conifer distribution over the long term. Large areas of the boreal forest appear to be sensitive to climatic change, especially where the annual precipitation minus potential evapotranspiration is less than 15 cm. “If global change leads to substantially drier conditions, then there could still be eventual losses of forest cover from these low-elevation areas, possibly leading to fragmentation of the western Canadian boreal forest.” (Hogg 1994:1843).

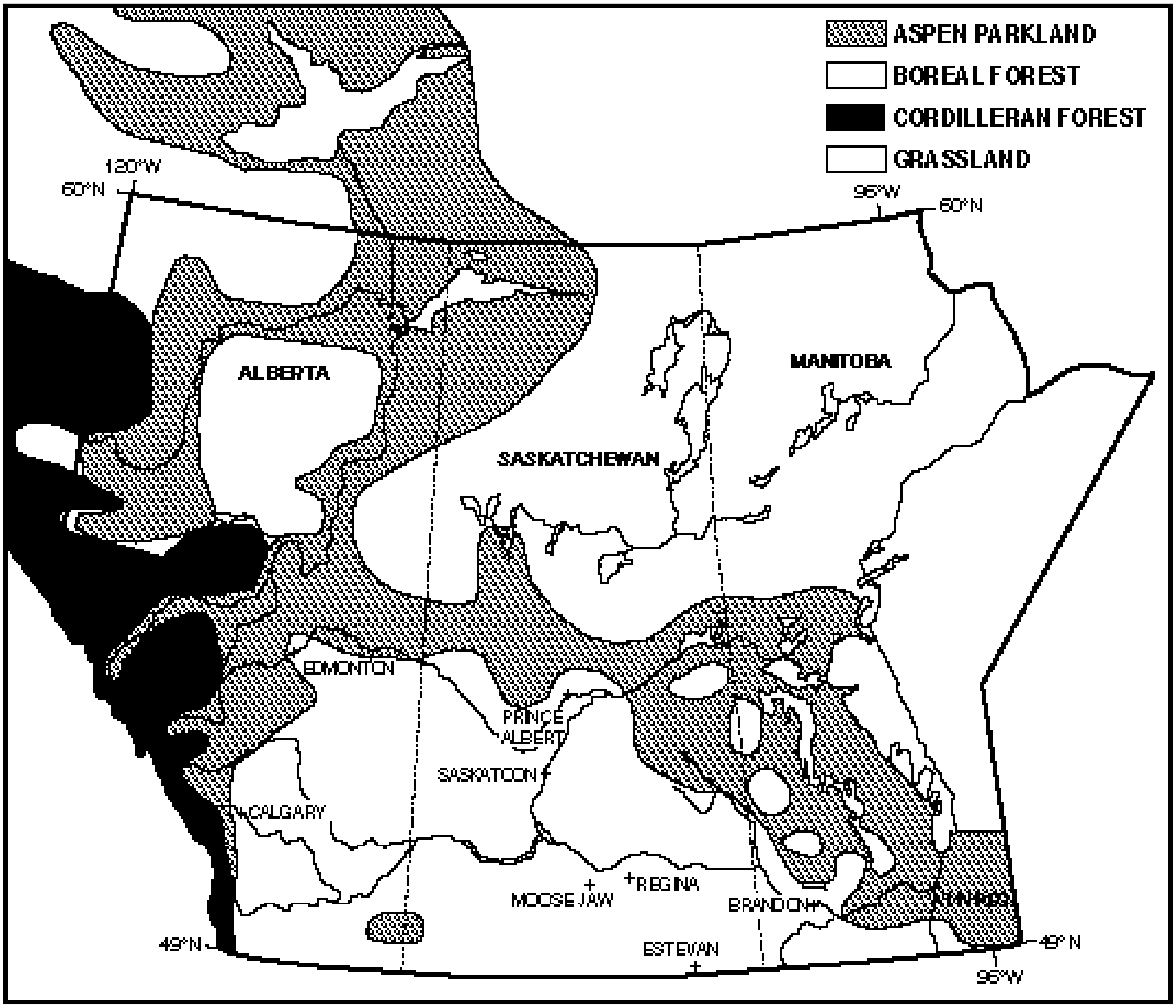
However, if their distribution is predominantly determined by fire regimes, the present zonation will persist, unless fire frequency increases (Hogg 1994). Fire frequency is expected to increase with increasing drought frequency because drought and fire are closely related in this region (e.g., Wittrock and Wheaton 1996). Therefore, if fires are not adequately controlled, they could be a mechanism of accelerating the northward shift of the boreal forest.

The increased carbon dioxide concentrations may act to offset the effects of drought. The direct effects of increasing carbon dioxide increase photosynthesis, growth and water use efficiency in many plant species (e.g., Lemon 1983). The author has not found any literature that presents model results for climatic impact effects on boreal forests including possible direct carbon dioxide effects.

There are many uncertainties about the direct fertilisation effects of carbon dioxide (Table 1). Serious reservations about the assumed benefits of such effects, or about how such data is used, have been expressed elsewhere (e.g. Sinha 1991, IPCC 1990). Also, carbon dioxide fertilisation is thought to have less effect in boreal than in warmer climates (IPCC WG II 1996). Others have argued that if this effect is included, the effects of other atmospheric pollutants and of decreasing stratospheric ozone depletion, for example, should also be considered (Williams and Wheaton submitted).

Hogg and Hurdle (1995) used the results of the Canadian Climate Centre’s model (Boer et al. 1992) with the climatic moisture index (Precipitation minus Potential evapotranspiration [P-PET]) to determine which areas of the boreal forest are sensitive to climatic change. The analysis indicated that the 11 percent increase in annual precipitation would not offset the increase in PET with the estimated warming of 4 to 5°C. This change would expose half of the western Canadian boreal forest to a drier climate, possibly analogous to the aspen parkland zone, where conifers are usually absent and aspen is limited to patches of stunted trees amid a grassland (Figure 2). “Future changes could result in permanent losses for forest cover following disturbance and an increase in the proportion of exposed edge habitat in remaining stands, where environmental conditions might induce additional stresses on tree growth. Thus if the predicted warming and drying occurs, productivity of aspen and other commercial species in the southern boreal forest would be greatly reduced.” (Hogg and Hurdle 1995:391).

Figure 2. Future equilibrium vegetation based on future changes of the climatic moisture index (precipitation minus potential evapotranspiration [P-PET]) in the western Canadian interior. (after Hogg and Hurdle 1995)



(after Hogg and Hurdle 1995)

More simulation models are now being run to estimate the responses of biomass and species composition to expected future climatic changes. Price and Apps (1996) used the FORSKA2 patch model for 11 locations along a northeast to southwest transect across the boreal forest in Saskatchewan and Manitoba. This model was designed to simulate landscape-level processes in boreal forest ecosystems. Its estimates of current biomass accumulation and functional types are very consistent with local inventory data.

Results of the FORSKA2 forest model differed according to the different climates of each of the four sets of general circulation model [GCM] results for a changed climate (Price and Apps 1996). The Goddard Fluid Dynamics Laboratory [GFDL] based climate scenario indicated the greatest change in species composition and steady state biomass (over 50 percent reduction), while the Oregon State University [OSU] scenario resulted in the least damage (an overall 40 percent increase in biomass). The other two GCMs produced overall increases in simulated biomass accumulation; results from the United Kingdom Meteorological Office [UKMO] and GISS climatic change scenarios were between these extremes. The type of climate forcing of the GCMs appears to explain these results. The GFDL results have a large increase in temperature (7.4°C) and only a 7 percent increase in precipitation, whereas the OSU results have a much smaller increase in temperature (3.2°C) and a much larger increase in precipitation (12 percent).

Price and Apps (1996) also examined northeast to southwest differences across the transect. The climatic scenarios generally resulted in minor changes in steady state biomass accumulation and species composition in the north. In the south, small to large increases were found with the GISS, OSU and UKMO and large decreases were associated with GFDL climates. FORSKA2 did not indicate a pronounced northward shift of existing vegetation zones under any of the future climate scenarios used. The reason is the invasion of *Pinus strobus*, a species not presently found in the BOREAS transect area. The increase in biomass for the GISS scenario in the south is entirely dependent upon this invasion. This indicates a response to warmer winters which permits species establishment of less winter-tolerant types.

Other experiments have indicated an increase in biomass except for areas with moisture limitations (e.g., Wheaton et al. 1987, Wheaton 1992), but Price and Apps (1996), discussed above, have provided much more detail in modelling, both in terms of biomass simulation and range of future climates used. Unexpected findings are the minor changes in the north, where ecosystem productivity is considered to be limited by low temperatures and the lack of northward shift of vegetation zones.

Lenihan and Neilson (1995) used the rule-based Canadian Climate-Vegetation Model [CCVM] to investigate the potential equilibrium response of vegetation for two climatic change scenarios (GISS 1988 and GFDL 1987). The CCVM is an improvement over equilibrium vegetation modelling for the purpose of climatic change experiments because climatic measures are more causally related to the growth, reproduction and survival of plants. Its simulation of current vegetation conditions accurately represents the observed distributions in Canada.

The CCVM projected northward shifts of the boreal forest and prairie grassland, especially for the GFDL scenario (Lenihan and Neilson 1995). This results in a reduction in subarctic woodland area. Mechanistic reasons are listed for the possible changes described. CCVM, unlike the BIOME modelling (Neilson 1993), projects boreal evergreen forest dieback induced by drought and a replacement by prairie grassland. BIOME results show little change in these distributions.

The CCVM results for both future climate scenarios indicate significant changes in species dominance distribution under equilibrium conditions (Lenihan and Neilson 1995). For example, the dominance of *Picea mariana* and *Picea glauca* could be reduced by 20 to 30 percent with a northward range shift of up to 800 km in the western boreal region. These shifts are driven by growing degree-day and summer actual evapotranspiration increases in the north. In the south, the driver is increased soil moisture deficits. Extensive changes in other species' distribution are also projected, with unique responses for each species. Constraints on the realism of the projections include the climatic projections, soil limitations, permafrost, competition, disease, insects, carbon dioxide fertilisation, extreme climatic events, migration, and many other relevant factors.

Concentrations of greenhouse gases are expected to increase beyond a doubling of carbon dioxide equivalent. Therefore impact experiments, especially for ecosystems such as forests with long rotational periods, should consider climatic changes beyond that point. Williams and Wheaton (submitted) used a biomass productivity climate model (Turc and Lecerf 1972) to examine impact results along a time series to a quadrupling of carbon dioxide equivalent. Two different GCM-based scenarios were used as well as arbitrary changes in precipitation to further assess sensitivity. The estimated biomass productivity increased to the doubling of greenhouse gases for the northern location (Uranium City) of the boreal forest in Saskatchewan, but decreased beyond that time (i.e., to 4 x CO_2). This was thought to be related to the midsummer decrease that is not compensated sufficiently by the growing season increase. The southern location (Prince Albert) experienced an increase in estimated biomass potential only to a 50 percent increase in carbon dioxide, and then little change was evident after that time. Uncertainties include interactions with disturbances and soil conditions.

Patch models of vegetation dynamics have been widely used to examine ecosystem sensitivity to past and future climatic change. A coordinated and standardised collection of experiments has been run and documented in a recent special issue of the Climatic Change Journal, including results for the Canadian boreal forest by Price and Apps (1996). Sixteen groups reported predicted ecosystem response results. Responses ranged from small to large depending on specifics of the current and scenario climates, and current vegetation structure. The main findings were that all of the models predicted important ecosystem structure changes resulting from climatic change, and explanations for the responses were often model-specific and linked to the type of formulations of key ecological processes.

Sykes and Prentice's (1996) results emphasise the potential complexity of transient responses to climate change, the long "memory" of undisturbed forest systems, and the importance of migration rate. Mature Picea trees are not at all negatively affected by the warming. If climatic change is too rapid for migration rates, naturally regenerating forests may become less diverse (early successional species dominance) and contain less biomass. More realistic models would explicitly represent the migration process. Migration rate may be a greater problem for managed forests which would react faster to climate.

Martin (1996) has used a sensitivity study with a physically and physiologically based, climatically sensitive numerical simulation model of forest dynamics [EXE] to investigate the role of water stress as an agent of rapid vegetation change. It helps explain the relative importance of temperature, water, and nitrogen limitations and shows that water stress is responsible for among the fastest vegetation changes. The transient climatic scenarios with gradually changing climates result in a higher net primary productivity [NPP] than the doubled CO_2 scenarios where the growth reducing effects operate during the entire simulation period. Martin writes that the most striking aspect of the results is the response variability for different species and different climatic scenarios. Post and Pastor (1996) also state that climate change initiates a complex set of direct and indirect responses that are sensitive to the exact nature of the climatic scenario.

European work has similarities to North American work in sources of uncertainties. Sykes and Prentice (1996) have modelled the controls on tree species ranges and transient responses to climate change of the boreal forest in Europe. They show that the degree of sensitivity of a certain site depends both on the climate change scenario and on the transient dynamics of the forest community. A highly uncertain future for the European boreal forest seems likely because of the uncertainties about the role of dispersal and changes in disturbance rates and because of the complexity and variety of transient vegetation responses.

Lindner et al. (1996) used the forest succession model FORSKA for two GCM based climatic change experiments applied to a west-east transect across central Europe. The climatic scenarios lead to reduced forest productivity and changed species composition on most sites. The improvements needed are the resolution of the climatic scenarios, and simulation of forest dynamics driven by climate variability and extreme events.

Predicting vegetation responses will require improved knowledge of ecological responses to climate. These include the effects of climate on regeneration and growth, forest succession, fire regimes, and the carbon budget in forests (Hogg 1996). Much of the work relating climate and vegetation gradients uses long-term mean climatic data and does not address the role of extreme climatic events such as frost and drought, evapotranspiration differences among vegetation types, and the role of disturbances (Hogg 1996). A wider set of climatic data, including extremes, should be used in further research.

Inter-scale analyses of past ecosystem responses to climate along with simulation modelling is an important route to understanding long-term processes. The Canadian Forest Service is currently using such approaches (Hogg 1996). Their modelling initiatives include a carbon budget model and several forest growth models (e.g., Price and Apps 1995).

Research has emphasised the steady-state conditions of both climate and vegetation because of lack of research tools and data. Price and Apps (1995) write that more understanding is needed of the short-term dynamic responses of the boreal vegetation to anticipated global changes, especially for the shorter term (50 to 100 years) and for the socioeconomic implications.

Price and Apps (1995) report that a suite of predictive models is being developed to better assess short-term (50 to 100 y) transient ecosystem dynamics and their implications for management and policy. The models are being based on field studies of past dynamics and current processes of the boreal and tundra biomes. These models will start to provide answers to many policy-relevant questions concerning current and possible future interactions between the boreal ecosystems and the global environment.

Here are some of the questions Hogg (1996) asks: Is the southern boundary strictly limited by moisture or a combination of effects with moisture and fire? Vegetation has a feedback effect on climate. How does the distribution of forest and grassland affect the climate? How would changes in vegetation affect the evolution of the changing climate? "In terms of vegetation-climate relationships, there are many such questions remaining, which can probably be addressed only through continued interdisciplinary research efforts, with a much greater emphasis on temporal scaling." (Hogg 1996).

As with other simulations of biomass and functional type changes, many uncertainties exist in terms of both the regional climate models as well as the forest models. Price and Apps (1996) list the forest modelling uncertainties as: disturbances (especially fire, insects, and diseases), species migration rates, soil condition constraints, and drought effects (e.g., on survival, regeneration). These are not accounted for in such simulations of biomass and other vegetation changes. Modelling results remain premature until these are considered. Therefore, it seems that we do not know whether biomass will increase or decrease and in which part of the forest, or whether zonation shifts would be encouraged by the shifting climate zones.

Although climate is one of the most important factors of change, it is only one of several factors. Therefore, a simple cause-effect relationship is unlikely. We should ask "How will climatic change affect the key factors and key processes?" What interactions are likely? Under the scenarios predicted by climatic change models, the boreal forest could be converted to grassland, and in a relatively short time, that is, much shorter than previous changes. The boreal closed-crown forest as we know it in the west could disappear, taken over by grasses and herbs adapted to periodic drought of the grassland climate.

Disturbances

"Wildfire is the driving successional force in the boreal forest and has remained so despite fire suppression activities and extensive harvesting. Insects and diseases also cause extensive damage" (Hall 1995).

Disturbances such as fires and insects are key factors in the health and growth of existing forests as well as in the success of future restocking efforts (IPCC WG II 1996). Tree mortality in the boreal shield ecozone is caused by natural factors such as insects, diseases, and storms. Annual tree mortality in the boreal shield ecozone ranges from nil to 2.5 percent. The highest mortality rates occur in trembling aspen and balsam fir and are caused by damage from outbreaks of the forest tent caterpillar, the large aspen tortrix and the eastern spruce budworm. Mortality in the boreal plains ecozone has been 2 percent or less annually since 1985. In this ecozone, mortality is mostly caused by natural thinning, insects, and diseases. No signs of pollution damage have yet been observed in the 70 boreal ecozone plots (CFS 1996*a*). Recent results from climatic impact work regarding disturbances are summarised in Table 2.

Fire

Most of the western Canadian boreal forest is of fire origin. Large scale natural disturbances are key factors affecting forest structure and successional development. Models are being developed to explore the effects of disturbance processes on spatial and temporal vegetation dynamics. Recent trends in forest fire activity have been concurrent with drought and warming trends in Western Canada in the past 20 years. Area burned, fire numbers and expenditures have exceeded expectations in the last 15 years (Canadian ad hoc GCOS Task Group 1995).

Very little research has been published that provides quantitative estimates of fire risk for climatic change. Wheaton et al. (1992) and Wittrock and Wheaton (1996) provide the most recent reviews and an update is provided here. The work cited in those reports stated that increased fire risk is expected with climatic warming scenarios. The only publications found with quantitative estimates for the area were Flannigan and Van Wagner (1991) and Kadonaga (1994).

Future climatic warming will change many aspects that influence the fire hazard. These include frequency and intensity of the hazard over time and space, quantity of available fuel, species composition, as well as fire season length, droughts, and lightning. The concern that boreal fire activity will continue to increase in the future is realistic. Human and ecological implications are serious. The boreal forest ecosystem is fire dependent, but more rapid increase in fire activity will stress the balances.

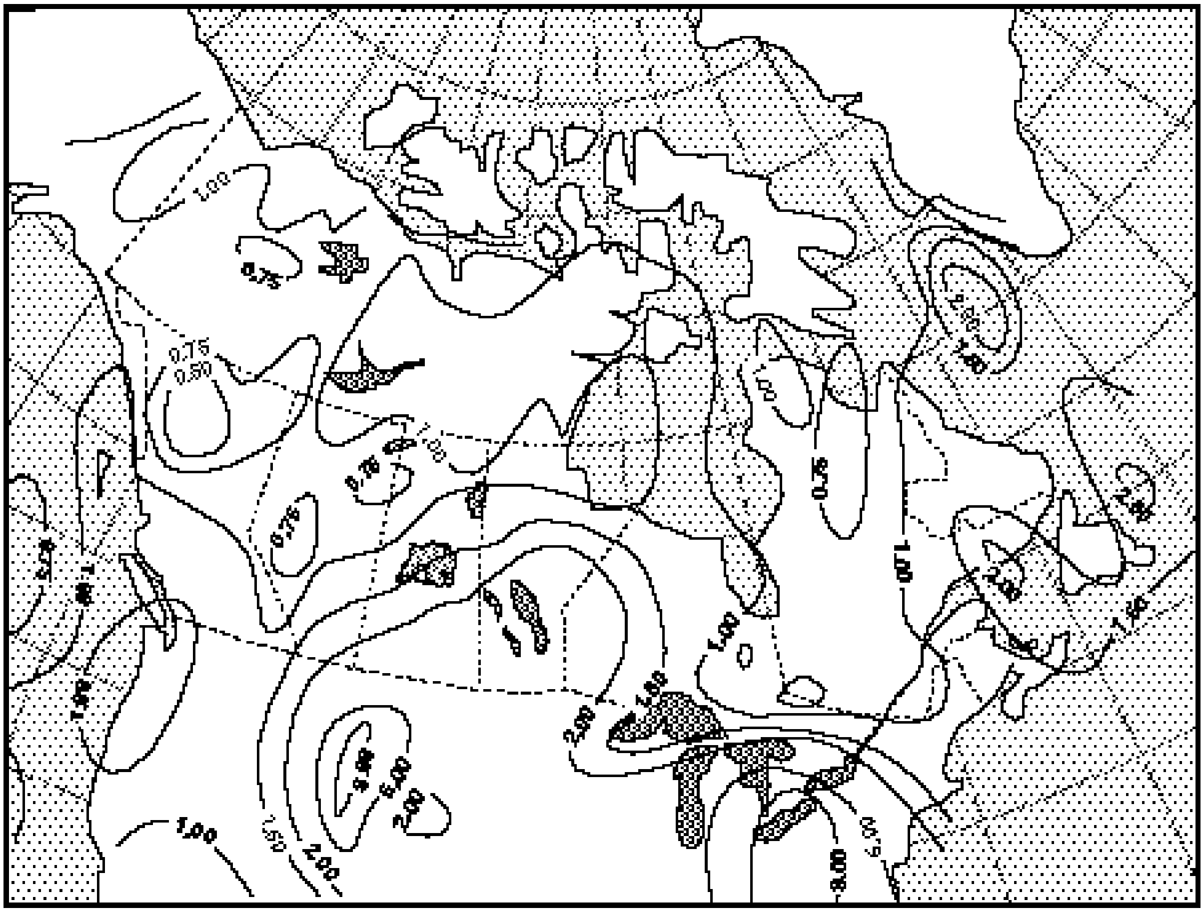
Stocks et al. (1996) examined the carbon budget implications of fire management in the boreal forest and concluded that more and larger boreal forest fires are expected in the future. A re-evaluation of protection priorities is required, because current suppression budgets would not maintain burned areas under a warmer climate.

Li and Apps (1995) state that it is vital to understand disturbance regimes and to include them in estimates of changes in the forest ecosystem induced by climatic change. Bergeron and Flannigan (1995) report that the effects of climatic change on forest disturbance are presently a major concern.

Flannigan and Van Wagner's (1991) results show a possible 46 percent increase in seasonal fire severity rating in Canada and a possible similar increase in area burned with a doubled carbon dioxide climate.

Bergeron and Flannigan (1995) used the Canadian GCM to examine the effect of climatic change on Canada's fire regime as indicated by the Canadian Fire Weather Index [FWI]. The FWI represents the intensity of a spreading fire. Increasing fire severity is expected with increasing temperatures if there are no changes in other factors such as relative humidity, wind speed and precipitation. The mean FWI calculated from the control climate scenario correlated reasonably well with the observed mean FWI. They found that the most striking feature of regional change was the dramatic increase in FWI and its components with the climatic change over the western Canadian boreal forest. The FWI was found to increase the most (double) on the southern boundaries, especially in Saskatchewan and Manitoba, and decrease to 75 percent of the current fire risk in northeastern and southwestern boreal Alberta (Figure 3). These results agree with aspects of other study results that indicate increased fire activity with climatic warming. Western Canada is the location of most of the fire activity historically. Climatic change will result in dramatic changes in the fire regime on a continental scale because of this increase in the west.

Figure 3. Fire Weather Index ratio (2 x CO_2/1 x CO_2) with increased global warming (Bergeron and Flannigan 1995).



(after Bergeron & Flannigan, 1995)

Fire climatic change research is in its infancy and should have much higher priority, especially for this study area. There are many reasons for urgency including: current and projected large increases in risk, human effects (economics [e.g., suppression costs, timber losses], communities, recreation, tourism, particulate pollution); fire as an agent to accelerate zonation changes; and climate feedbacks through changes in carbon budget, albedo and wind. Forest fires could be the early warning "bird", the first indicator of change. Global warming means reassessment of the way humans co-exist with fire and means changes in policy and research priorities.

Insects

"Insect populations have a substantial impact on Canada's forest. They are a dominating disturbance factor and during outbreaks they can cause tree mortality over vast areas of forest. If the predicted climate changes take effect, the damage patterns caused by insects may be drastically altered, especially for the many insects whose occurrence in time and space is severely limited by climatic factors." (Fleming and Volney 1995).

Fleming and Volney (1995) examined the effects of climatic change on insect defoliator population processes in the boreal forest. Changes in disturbance regimes such as insect outbreaks are seen as the driving force to effect many of the expected forest ecosystem function and composition changes (e.g., Kurz and Apps 1995). Insects exert a major influence on forest productivity. Annual forest losses from tree mortality from insect attack in Canada are estimated at 51.0 million m^3 per year. These losses are 1.5 times those due to wildfire and are one third of the annual harvest volume (Hall and Moody 1994).

The spruce budworm is responsible for more losses in Canada than any other insect. The spruce budworm range matches most of the range of the white spruce in the boreal forest. It can kill almost all the trees in dense, mature stands of fir during uncontrolled outbreaks. Periods of outbreaks (high population densities) usually last for 5-15 years, interspersing periods with low populations of 20 to 60 years. Per capita growth rate increases occur with warm, dry conditions. Under climate warming, higher temperatures should increase rates of foliage development and would reduce the time when the insect has access to immature foliage. This may reduce breeding success in some insects. But the budworm is so well synchronised with tree growth that weather may make little difference. Relationships with natural enemies may also change with climatic change. If the host develops much faster than the parasitoid, then the host may completely escape from its effect (Fleming and Volney 1995).

A changing climate is expected to bring generally drier conditions with an increased likelihood of droughts and heat waves. The survival and fecundity of insect herbivores often improves on drought-stressed trees. Therefore, the boreal forest may suffer increasing insect pest problems with a warming climate. Plants stressed by drought provide an ideal thermal and feeding environment for many insect pests. Synergistic interactions between drought induced changes may in turn allow the budworm to improve its performance to the point that it can escape natural enemy regulation. Then outbreaks may become more frequent and severe (Fleming and Volney 1995).

Extreme weather events, especially late spring frosts and drought, shape budworm effects. Late spring frosts are associated with the end of outbreaks. As the climate warms, the frequency of late spring frosts will decline, and population densities of spruce budworm will remain high for longer periods in northern white spruce stands (Fleming and Volney 1995).

Many insects are also preadapted to climate change. Also, if the insect's geographic range is large, common genotypes from warmer areas may readily invade cooler areas as the climate warms. Evidence of accelerated phenological development has already been found. This is an indicator of recent insect response to climate warming. Fleming and Tatchell (1994*a*, *b*) found that flight periods have moved ahead by an average of about 3-7 days over the past 25 years.

The white pine weevil reduces growth in spruce and pine throughout North America. Sieben et al*.* (1994) estimated the effects of climatic change on the white pine weevil hazard in the Mackenzie River Drainage Basin. They used growing degree-day accumulations above 7.2°C as an indicator of the range of the weevil hazard. A climate warming of 2.2°C increased the area of the high hazard class from 24 to 51 percent. The estimated weevil range also shifted northward and upward in elevation.

Other insect ranges are also expected to shift northward with shifting climatic zones (e.g. Wheaton et al*.* 1992). Some shifts have already been noted. For example, in 1995, a major outbreak of forest tent caterpillar was observed for the first time in the Northwest Territories, in the Fort Liard area (Brandt et al*.* 1996). Such northward invasions of insect populations with a changing climate could have major impacts.

Could the future drought conditions in combination with insects and diseases cause decline and dieback? Neilson (1993) suggests that forests could undergo significant drought-induced decline and dieback. Also, drought-stressed trees are more susceptible to other disturbances such as insects and fires. Management of such forests and many other adaptive strategies, such as thinning for example, would be required to minimise losses.

Windstorm-caused blowdown

What is the current damage by blowdown in the boreal? Blowdown by windstorms damages much less forest than do fires. However, most boreal tree species are shallow rooted and susceptible to wind damage. The higher expected future temperatures, higher tropopause, and cooler stratosphere could increase the frequency and intensity of destructive thunderstorms. This would increase the damage by blowdown.

Carbon budget

"Forests play an important role in the global carbon cycle, fluctuating between being a sink and source for CO_2*. They absorb and store* CO_2 *during growth cycles, and they release* CO_2 *to the atmosphere during respiration, decomposition and*

burning. The boreal forest is one of the world's largest ecosystems and is the dominant forest region in Canada, Alaska and Russia. Canadian scientists are working with scientists from the United States [USA] and other countries to improve our understanding of the role of the boreal forest in the global carbon cycle and the interaction between forests and the Earth's climate." (CFS 1996:44)

Boreal, tundra, and subarctic (high-latitude) terrestrial biomes cover about 25 percent of the Earth's land surface, and contain an estimated 800 to 900 Pg carbon. This is about one third of the global terrestrial ecosystem total. Plausible changes in vegetation structure may result in both positive and negative climatic feedbacks. Some of the more immediate and transient feedbacks include carbon dioxide release from drier organic soils and methane releases from melting permafrost (Price and Apps 1995).

A large-area process-based Carbon Budget Model of the Canadian Forest Sector (CBM-CFS) is being validated. This model provides an integrating framework for estimating the contributions of vegetation productivity and other ecosystem processes to regional and national carbon budgets. Regional-scale implementations of the model are being used to examine the carbon budget sensitivity to transient changes in climate and resource management (Price and Apps 1995).

Krankina and Harmon (1995) write that "One of the most important questions facing ecologists today is the role of the biota in the global carbon cycle." We still do not understand the current role of forests in controlling the global carbon cycle. This uncertainty is reflected in the fact that 20 to 50 percent of the annual fossil fuel carbon cannot be accounted for and that forests are described as both sources and sinks, depending on the study.

Forest land management affects the net exchange of carbon between the atmosphere and the forest ecosystem. The types of management implicated include harvesting, silviculture, site preparation and forest products utilisation (Kurz and Apps 1993). Krankina and Harmon (1995) found that intensive forest management including short harvest rotations, thinning and wood salvage reduces dead wood carbon stores from 5 to 40 percent of the potential level of undisturbed old-growth boreal forests (northwestern Russia) and that natural disturbance increases the dead wood carbon pool by a factor of two to four.

Forest dynamics as affected by climate and other factors could significantly affect the carbon content of the atmosphere. Kurz and Apps (1995, 1996) analysed the range of responses of the forest carbon budget to different management options, including reducing disturbance rates, accelerating regeneration of disturbed areas, and converting non-stocked forest land to productive stocked forests. Changes in the area disturbed (mostly by wildfire and insects) greatly affect biomass and soil carbon dynamics and therefore the annual net carbon exchange with the atmosphere. Disturbance areas have greatly increased in the 1970s and 1980s as compared to the previous 50 years. The five-year average of the area disturbed annually in the Canadian boreal forest was more than twice as high, at 3.9 Mha y^{-1}. Reducing the rate of disturbances increases the rate at which forests switch from a carbon source to a sink, and vice versa. Their results showed the estimated 50 y carbon budget of the six management options ranged from a net source of 1.4 Pg carbon to a net sink of 9.2 Pg carbon.

Scenarios of future trends in disturbance regimes indicate that the carbon dynamics of Canadian forests will change again during the next few decades (Kurz and Apps 1995). Biomass productivity and mortality are fundamental to determining the carbon dynamics of forests. There is an urgent need for improved knowledge of these processes (e.g., Shvidenki et al*.* 1996). A large wild card appears to be the balance between climate-induced growth and disturbance (Tian et al*.* 1995). Which will predominate, and where and when?

Economics

Canadian forests have important economic roles, as stated earlier. The forests also support several other activities including tourism, recreation and native self-reliance. The non-market values are also estimated to be high (van Kooten in Wheaton et al*.* 1987). Forest economics for the three prairie provinces that are the study area are provided in CFS (1996). For example, the direct and indirect employment is 62 000 for the prairie provinces. The economic importance of the forest resource is especially clear in the many communities that depend directly on the forest.

What changes in these statistics can be expected with the types of climatic changes foreseen? How sensitive is the forest industry to these changes? Would most of the effects be direct through changes in growth patterns or indirect through forest disturbances and changes in infrastructure (roads) and demographics or policies for greenhouse gas management? Currently there appears to be little work examining these questions and few answers. Selected key papers are included here.

Van Kooten (in Wheaton et al. 1987) was one of the first to explore the forest economic impacts of climatic change for the study area. This work was expanded in van Kooten and Arthur (1989) who used applied welfare economic models to assess the economic benefits of climatic change on the boreal forest. Using the productivity increases estimated in Wheaton et al. (1987) for some of the models, they estimated the economic welfare impacts for Canadian and the US producers and consumers. The results indicated that, in both countries, consumers are the major beneficiaries of such changes and that producers experience welfare losses. If the effects of international trade on both producers and consumers are considered, increased productivity may reduce the overall welfare of Canadians, to the overall benefit of the trading partners.

Binkley and van Kooten (1994) discuss the policy questions and the co-evolutionary development of the climate, terrestrial biosphere and the forest sector. They identify several gaps in research regarding adaptation and the development of policy options. They found that none of the studies examined explicitly traced the effect on the forest of adaptive changes such as those induced by policy. Promising policy options include carbon tax and materials policies. They emphasise the importance of including the non-timber aspects of forests in analyses because these values exceed the timber values by wide margins in many settings. Also, the non-timber aspects may be less able than forest industries to adapt to a changing climate.

The Mackenzie Basin Impact Study [MBIS] includes socio-economic implications of climatic change for the forest sector. Rothman and Herbert (1997) examined the current role of forests and existing policies in terms of a changing climate. They confirm that very little work has been done in this area of social and economic impacts and that the existing research has emphasised basic economic parameters such as prices, harvests, supply, and consumer welfare.

Rothman and Herbert (1997) summarise key biophysical impacts from the MBIS work:

- potential productivity of younger trees is increased more than of older trees.
- deciduous species have better potential growth than coniferous species;
- area burned increases to 2.5 times by 2050.

These patterns are consistent across the basin, with considerable local variation, and combine to cause a shift toward younger trees and an overall significant decline in standing volume. These changes are expected to be more dramatic and occur earlier towards the south.

The increase in fire hazard affects forest management costs to suppress or manage these disturbances. The expenditures form a large share of total forest management outlays. The average shares of total forest expenditures for protection from pests and fires were 63 percent and 36 percent for Saskatchewan and Alberta, for example, for 1988 to 1993. In the future, control expenditures will have to increase significantly or much larger areas will be affected by disturbances (Rothman and Herbert 1997).

Changes in productivity affects several aspects of forest management, including annual allowable cuts and therefore harvest levels. The MBIS work implies a decline in annual allowable cuts due to a changing climate, mostly related to declines in volume and increases of disturbances. Increased management, especially of the disturbances, may alleviate the declines, but will also raise the costs significantly (Rothman and Herbert 1997).

Biophysical impacts also affect optimal rotation management. This usually only considers the timber value, but other environmental amenities are increasingly being examined and will affect optimal rotational ages. Increases in losses from disturbances will lead to a shorter optimal harvest (Rothman and Herbert 1997).

Rothman and Herbert (1997) are also among the few authors to consider the concurrent developments, including land treaties, international trade, technological trends, and societal attitude shifts (to ecosystem health and diverse uses as opposed to sustainable yield of timber). These forces will have effects on costs of harvesting and the structure of production. Relative effects compared to climatic change need to be determined. They conclude that:

> “The actual effects that changing climate will have upon species mix, AAC [annual allowable cut] determinations (and thereby harvest levels) and optimal rotations are unclear, but potentially significant. Whatever the impact, given the similar time horizons of the impacts of changing climate and many forest management policies ignoring its effects may lead to a high price in the long-run.”

Except for the few publications cited here, it appears that nothing else has been published in Canada regarding this topic (van Kooten 1997 p. comm.). Considerable investments are being made in reforestation, management and harvesting of forests, and in forest-based industries and communities. Climate change has implications for the costs and type of forest management and investments. For example, seedlings currently being planted will only reach about half of their harvestable age by about 2030 AD. At this time, they would be growing in a changed climate that may be more or less suitable to them and likely be exposed to a higher risk of disturbances. Maini (1990) writes that strategies to protect such investments should be developed. If climate estimates are correct, within 25 years we will have to deal with a range of new and complex issues around forest disturbances, vegetation competition, and the adaptation of harvest machinery and equipment. To compound the problem, the forest sector needs a longer lead-time than many other sectors to address issues determining the growth, health, and survival of forest ecosystems (Maini 1990).

What interactions with other sectors may be expected? Wheaton (1992, 1994) has considered global climate change interactions with several other sectors in a qualitative manner. This issue should be examined much more comprehensively and modelled quantitatively. This work would reduce the surprises associated with these complex interactions.

CONCLUSION

Although several characteristics of the boreal forest were examined in terms of a changing climate, research on many important aspects appears to be sparse. One of these is soils. Except for the carbon budget research reported, such soil research appears to be sparse. Considering the importance of disturbance in the region, both in the present and the future, it is surprising that more research has not been devoted to the topic. Also, biodiversity and integrated assessment work appears to be rare; no work other than Wheaton (1994, 1996) for integrated assessment and Wheaton (1993) for biodiversity was found. That work considered climatic change as part of an integrated forest resource management planning document for Saskatchewan.

Impacts on the forest ecosystem of a changing climate are not expected to be smooth and gradual. Changes are anticipated for the boreal forest, and adaptive strategies must be developed and tested. Changes may be subtle for some time, until ecological thresholds are reached, feedbacks intensify, or until disturbances occur. Neither will changes be easy to predict in most cases. Complex interactions, feedbacks, and nonlinear relationships will cause surprising results. Therefore adaptive strategies need to be robust and flexible.

ADAPTATIONS

Questions to ask include: What adaptations are required? How adaptive is the sector? Very little published research was found regarding forest sector adaptations to climatic change. Several adaptive strategies were mentioned in the impact work discussed above. Singh and Wheaton (1991) have summarised several adaptive strategies.

Binkley and van Kooten (1994) provide a more recent concise summary: “The forest products industry can adapt to ecosystem changes by salvaging dying trees, replanting with better-adapted genotypes or species, or moving to those places where timber becomes more abundant.” They are less optimistic about adaptation for non-timber aspects, such as biological diversity. Rothman and Herbert (1997) suggest adaptation options such as using exotics on the southern edge to compensate for the productivity decline. Such an option may be useful to the forest industry, but the impacts on the non-market values, such as recreation, are also important to consider.

Adaptive actions that deal with climatic change and have other benefits, such as improving forest health and productivity, are recommended. A list of these possible "no regret actions" from the Pacific Northwest Forest Management Conference includes implementing uneven forest age management, maintaining an over-story cover, managing for several species, altering harvesting regimes to protect soils and maintain productivity, managing forest fuel build-up, and developing silvicultural alternatives to fire's role in ecosystems (Wall 1993). These actions attempt to mimic natural processes.

Management of the forest for non-timber and non-market concerns is also required and should be modified to deal with climatic change. These issues include carbon storage, water quality and quantity, soils, air quality, and biodiversity. Conflicting competing demands will be increasingly imposed on the forest and will require innovative management responses and the application of much more knowledge than we currently have. Adaptation strategies will have to include all aspects of the forest ecosystem with harvesting, reforestation, utilisation, and protection strategies. Other interests include wildlife and fisheries, recreation, and communities (Hall and Carlson 1990).

Adapting to a likely increase in disturbances

Management to protect the forest from stress will be required including (Hinckley et al. 1993):
maintaining landscape corridors, promoting landscape patterns that reduce the spread of disturbances
protecting photosynthetic capacity and soil fertility at the stand level by protecting habitats required by:

- natural enemies of forest pest
- maintaining or improving biodiversity
- maintaining or restoring tree vigour through practices including thinning, and
- avoiding clear cutting harvests to keep some cover of mature trees.

Recommendations from the Pacific Northwest Forest Management Conference (Wall 1993) for dealing with fire include managing stands and landscapes to reduce the likelihood of crown fires and large area fires, managing forest fuel, prescribed burning, preserving and enhancing biodiversity and managing forest landscapes that are becoming increasingly fragmented.

More intensive forest management may tend to reduce the risk of disturbances. An improved access network, for example, would facilitate fire suppression (Shelley 1997 p. comm), but it may increase human-started fires. Also second and third growth rotation may be less homogenous than current forests and therefore less susceptible to fires (Shelley 1997 p. comm.).

Although much of the boreal forest is not managed, the amount of managed forest is increasing. There are many questions about the relationships among a changing climate, forest and management including:

- how can the forest be better managed in order to reduce the negative effects of climate and increase the positive effects?
- will future management be able to offset the projected negative climatic effects?
- what types of future management are required to cope with a changing climate? How practical and economical are they? Are they appropriate to the study area?
- do we have sufficient management knowledge and tools? For example, genetically improved stock would be needed for productivity with increased droughts (Shelley 1997 p. comm.).

Management may tip the balance in the net outcome of the positive and negative climatic impacts. Therefore, it has an important role.

Research must be intensified on the relationship of forests, and disturbances with climate (Harrington 1989). Such information is vital to wise resource and adaptive planning. The effect for the western boreal forest of the 50 percent decline in summer soil moisture projected by Manabe and Wetherald (1986) would have devastating consequences, especially in terms of area burned by fire, insects, and of regeneration.

RECOMMENDATIONS (RESEARCH, MONITORING AND POLICY) AND CONCLUSION

"The major conclusion reached at the symposium was that, although there is much uncertainty

associated with the scientific debate on how quickly the climate is changing, forest managers need not and should not wait for conclusive resolution in the scientific arena. Managers must adopt a working hypothesis that significant climate change is probable in the near future, and they need to take appropriate actions now to reduce the threat to sustainability of the forest resource, especially where such action is also beneficial for addressing concerns other than climate change." (Wall 1993)

The future of the boreal forest appears quite uncertain in the face of climatic change. The forest may be increasingly shaped by climatic induced growth, disturbance, decline and mortality. Forest management may become a more critical factor.

Specific research recommendations are made in the preceding sections, where their context is explained. More general recommendations are included in this section. Uncertainties in Tables 1 to 3 should be carefully examined for additional recommendations. The major research concentrations should be: climate forecasting and scenario development, forest response forecasting (physiology, reforestation, tree variations, pollutants, fire, insects, diseases, forest decline), monitoring, mitigation, carbon budget, and socioeconomics.

Continuation and expansion of biophysical monitoring is urgently needed to improve knowledge about sensitivity and to find out what effects are already occurring as a result of the currently changing climate.
The early stage of the modelling framework used to assess the likely fate of the world's forests severely limits impact and adaptation assessments. IPCC WG II (1996) states that a consistent and comprehensive research strategy is needed to improve understanding of:

- the ecophysiological response of trees to changing climate and carbon dioxide concentrations;
- the relationship between tree growth and transient forest dynamics; and
- the influence of a changing forest on the global carbon budget and its feedback. Process-based terrestrial biosphere models of ecosystem dynamics are required to improve the overall modelling framework which would allow better assessments of forest interactions with climatic change.

Needless to say, the questions that guided the objectives of this work are far from completely addressed with the current available literature. The literature reviewed emphasises several main research, monitoring, and policy questions that require priority action. Sample questions include:

- what is the nature of the current interactions between climate and the boreal forest ecosystem? What critical monitoring needs are not being met? How fast are conditions changing?
- how should climate scenarios be developed to better reflect the range of possible futures
- what are the likely effects of forest ecosystem changes on other sectors?
- what are the shorter term transient (5 to 50 year) interactions expected between climatic variability, especially extremes such as drought, and the forest ecosystem? Currently, monitoring and research tools limit this understanding.
- what is the net effect of changes in growth and changes in disturbances over the long and short terms? Disturbances have a main role, especially in this study area, and the climate-disturbance models are mostly in their early stages of development.
- what adaptive strategies are available? What ones are required? How well do they work? What are the linkages with mitigation? What are their socioeconomic implications? This area of research appears to be limited.

In conclusion, the global biosphere is clearly very sensitive to climatic perturbations, but our present understanding of the interactions among changes in climate, elevated carbon dioxide concentrations, and soil nutrient dynamics is limited. This seriously constrains our ability to build models to make confident predictions of the specific responses of forest ecosystems to expected climatic changes (e.g. Price and Apps 1996). Responses of productivity, for example, are very variable, depending on climatic scenario and vegetation impact model used. It is clear, however, that research formulation and implementation, impact assessment, and adaptive strategy development regarding climatic change and variability appear to be in their early stages. Many key policy and research questions remain priorities.

The western Canadian boreal forest is a key area for further work because of the combination of the large climatic changes expected, the greater role of disturbances, and its role as a potential carbon source or sink.

ACKNOWLEDGEMENTS

The following people provided useful comments and references: Ross Herrington, Ted Hogg, Dale Rothman, Neil Shelley, Jeff Thorpe, and Casey van Kooten. I thank B. Tacik for editing, L. Crone for word processing and bibliographic work, J. Raven for obtaining publications, and J. Mamer for printing. Funding was provided by Environment Canada and the Prairie Adaptation Network (Saskatchewan Energy and Mines and Saskatchewan Research Council).

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APPENDIX C

ENERGY ON THE PRAIRIES

PRAIRIE ENERGY STUDY

ENERGY ON THE PRAIRIES

PRAIRIE ENERGY STUDY

Malcolm Wilson
Saskatchewan Energy and Mines
Regina, Saskatchewan

and

Elaine Wheaton
Saskatchewan Research Council
Saskatoon, Saskatchewan

The authors wish to acknowledge the assistance provided by Linda Hutchinson, Morgan MacRae, Grant McVicar, Don Macdonald, Gary Webster and Abha Bhargava in preparing this chapter. The opinions presented in this chapter are, however, those of the authors alone.

INTRODUCTION

Energy is the lifeblood of the Prairies. Without energy, commerce would come to a standstill and living would be effectively impossible in the winter. In short, a competitively priced, reliable supply of energy is essential to human and economic activity on the Prairies.

This chapter attempts to review all the energy sources, present and future, and energy utilization in the three Prairie provinces, together with the factors that impact on the demand for energy. It also attempts to evaluate the effect on the energy sector of a changing climate and adaptive strategies implemented by other sectors of the economy. It should be noted that the infrastructure developed by the energy sector has an extensive lifetime, one that could see adaptive changes in other sectors of the economy emplaced while the energy infrastructure continues to be utilized.

The production and use of energy results in the vast majority of Canada's current greenhouse gas emissions. The role of energy industries in dealing with climate change has, therefore, traditionally been viewed as one of undertaking mitigative activities. Indeed, the energy production sector has been among the most responsive of industry sectors to the national call to voluntarily implement measures to reduce energy related emissions as evidenced by action plans and progress reports submitted to the Voluntary Challenge and Registry[1]. Investigating adaptation is complementary to undertaking mitigative activities. It is a recognition that we are likely to be committed to some level of climate change due to the gases already in the atmosphere and to increasing emissions on a global level. In effect, undertaking analysis and implementation of adaptive strategies is a risk management approach to the issue of potential climate change; an approach that embodies mitigative and adaptive responses.

Most of the climatic change impacts studies relevant to the Prairie Provinces have focused on agriculture and forestry. Very little research has been done for the other sectors (Wheaton et al. 1992). The work that has been undertaken tends to emphasize the climatic effects on building energy utilization (space conditioning or heating and cooling), and particularly on the electrical sector for supply side issues. As a result of the material available, this chapter draws heavily on

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[1] The Voluntary Challenge is a national program designed to gain support from the private and public sector for emissions reduction on a volunteer basis. The Registry records the actions undertaken and the progress made to reduce emissions.

the electrical sector, particularly for illustrative examples. Other aspects, such as effects on renewable energy, have been neglected. Indirect effects created by other sectorial adaptations have been essentially ignored. As energy using sectors, such as forestry and agriculture, adapt to climatic change, interacting impacts on energy are expected.

Estimates of possible impacts of global warming, including problems and opportunities, plus other questions that frame the objectives of this chapter can be addressed only from a limited perspective due to a lack of information in the literature. Key questions include: How sensitive are aspects of the energy sector to climatic variations? What are the estimates of impacts of global warming on the energy sector over the next 50 to 80 years? How would these energy changes affect other economic sectors and the environment? For example, will increased summer energy demand for air conditioning affect energy availability for increased irrigation? These are the interacting and higher order effects that have previously been neglected (Wheaton 1994). Changes in other sectors would also be expected as they adapt to a changing climate. How will these interacting changes affect the energy sector? How will non-climatic factors such as population growth, changing demographics and changes in technology affect climate and energy interactions? Which adaptive strategies should be developed now and which can wait? (Strategies that help with current climate variability should receive priority.)

ENERGY AND CLIMATE INTERACTIONS

Climate and energy have many complex direct and indirect interactions (discussed more fully below). Limited study has been undertaken for each Prairie Province to examine the potential implications of future global warming in the energy sector. Raban (1991) examined the climatic change-hydroelectric production connection from a Manitoba Hydro perspective. He concluded that "Manitoba Hydro's main functions are all very closely associated with our climate." A summary of effects of climatic change on Manitoba Hydro follows:

- diminished river flow and its effect on hydraulic generation is thought to be the most significant. It could make the current planning criteria for new plant and operating practices inadequate.
- multiple freeze-ups and break-ups would reduce winter hydraulic capacity.
- transmission line icing would decrease performance of transmission facilities.
- decaying permafrost would destabilize towers and other structures.
- increased air temperatures would increase conductor resistance and result in increased energy losses.
- increased winter temperatures would adversely affect the construction and use of winter roads, thereby reducing winter shipping and maintenance. (Many of Manitoba Hydro's facilities are in remote northern areas.)
- decreased winter heating loads and increased summer air conditioning loads. The net effect should be a reduction in annual peak load. The correlation between air temperatures and load in Manitoba is good; therefore, the sensitivity of load to changing temperatures is high.
- the cost of energy supply for long-term firm export contracts was forecast to increase with climatic warming.

Indirect effects include:

- mitigation policies could result in restrictions on fossil fuel consumption, resulting in an increased demand for other energy sources such as hydroelectricity.
- changes in social, agricultural and industrial activities could affect Manitoba Hydro's business.
- climatic change impacts may be more adverse in surrounding jurisdictions; in this instance, Manitoba may enjoy a competitive advantage.

Implications of global warming for the energy sector, in particular the electricity supply sector, in Saskatchewan were studied by Wittrock and Wheaton (1992) as part of a broad assessment of environmental and economic factors. This work used a literature review and expert judgment approach. Factors considered included energy production (hydropower, thermal power, and renewables), consumption, greenhouse gas emissions, energy efficiency and conservation. Emissions were considered because of the possible effects of global warming and mitigation strategies on the source of power generation. For example, possible reduced hydropower production caused by decreasing water flow in a changing climate could be compensated for by increasing thermal power production resulting in an increase in fossil fuel consumption and greenhouse gas emissions.

The possible impacts of future climate change on the Saskatchewan Power Corporation (SaskPower) for both thermal and hydropower are summarized in Table 1 (Prasad in Wittrock and Wheaton 1992).

Table 1. Possible impacts of climate change on hydro and thermal power generation

Policy Issue	Possible Impacts of Climate Change	Confidence
Hydro	The increase temperatures will lead to increased evaporation and irrigation from reservoirs. This may be offset by increased precipitation.	Medium
	Increased evaporation and irrigation will mean lower volumes of water and lower generator efficiencies for hydro generation.	Medium
	Climate changes expected for Alberta are important factors for hydro generation in Saskatchewan.	Medium
Coal Fired	Increased ambient air temperature will cause increased cooling water temperatures. Increased fouling as a result of increased temperature.	Medium
	Evaporation from cooling water reservoirs.	Medium
	Higher cooling water temperature may cause generating units to be derated due to higher back pressures.	Medium

(Prasad 1991, SaskPower, p.comm. [Wittrock and Wheaton 1992:95]).

Note: Prasad, SaskPower, was considering Saskatchewan's case here, but the table is also appropriate for Alberta and Manitoba.

An assessment of possible impacts on the energy sector in Alberta was undertaken by Acres International Limited and summarized by Goos (1989). The findings were based on the use of the Goddard Institute for Space Studies results for a 2xCO_2 climate simulation:

- net saving of about 0.5 percent of total electrical consumption resulting from the balance of the decrease in winter months and increase in summer months. Heating degree-days were projected to decrease by 20 percent.
- natural gas consumption would also flatten out, decreasing in winter. About 80 percent of the use is for heating and this amount would decrease by about 20 percent.
- overall system efficiency would increase (investment saving of over $300 million).
- marked shift in electrical energy requirements within specific sectors. For example, irrigation energy demands could increase by 20 percent.

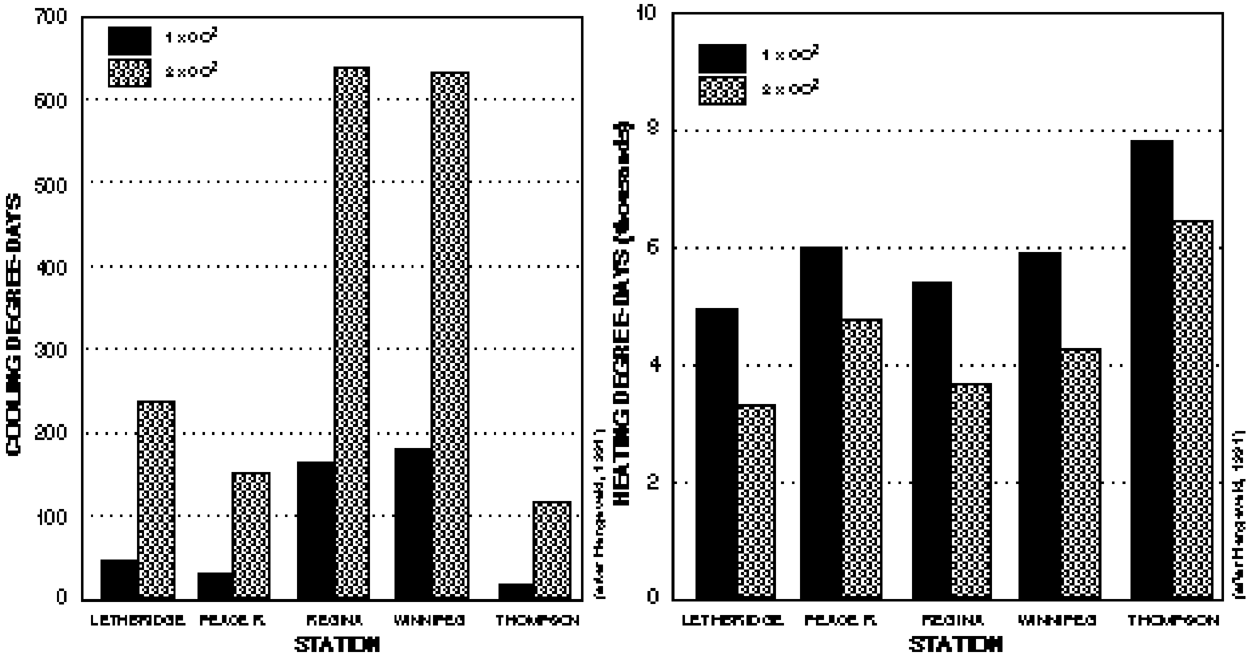
A significant potential impact on hydropower production for all three provinces would occur indirectly through the effect of droughts and increasing temperatures on river flow. Glaciers are an important water source that have undergone significant change. A general global deglaciation trend has occurred since the "Little Ice Age" (ref-Mike IPCC96 or?). Canada's extensive glacier resources are no exception. Glaciers in the eastern Rocky Mountains have lost between 25 and 75 percent of their Little Ice Age maximum volume over the last century. This trend will augment stream base flow in the shorter term (20 to 30 years). In the longer term (30 to 100 years) the reduced melt volumes from glaciers will reduce river flow, particularly in summer, from these sources (Demuth 1996) .

The implications of reduced glacial mass are important for hydro-power generation, reservoir management, habitat maintenance, agriculture, recreation and other sensitive sectors. Loss of base stream flow is especially important during dry summers. Decreased base flow contribution and changes in timing would influence hydropower reservoir operating strategies in preparation for periods of peak winter consumption, for example. Such effects would tend to diminish with distance from the eastern slopes (Demuth 1996, Demuth p. comm. 1997).

In summary, initial efforts have been made to assess the interactions of climate and energy in the Prairies with an emphasis on future global warming. However, these efforts are only preliminary and many important research questions have not been adequately addressed.

Hengeveld (1991) has examined the topic across the Canadian Prairies, but only for selected sites. Besides the work by Raban, he appears to be among the few using a quantitative approach. He focused on the strong association between temperature and heating/cooling (space conditioning) of buildings. Hengeveld used these correlations to model the increase of electrical use with increasing temperatures from climatic change scenarios for five Prairie stations (Lethbridge, Peace River, Regina, Winnipeg and Thompson). Regina showed the largest decrease in heating degree days, followed by Lethbridge and Winnipeg (Figure 1). Cooling degree-days increased, and the change is more dramatic than for heating degree-days.

Figure 1. Estimates of the effect of climatic warming on cooling degree-days and heating degree-days at five Prairie locations



Source: (Hengeveld 1991)

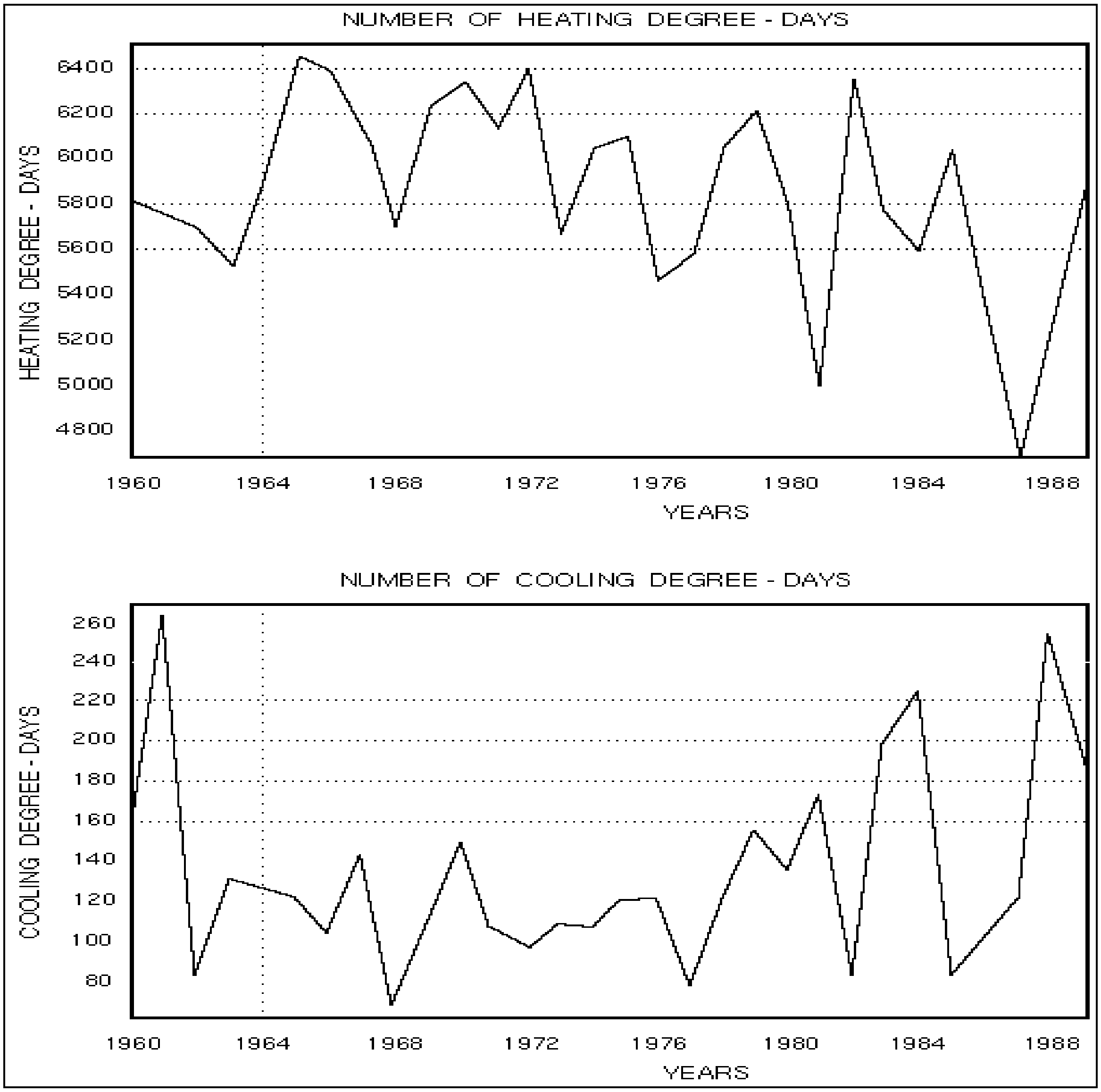
Hengeveld (1991) also pointed out the effects of climate on agricultural energy use. The indirect effects of climate through its effects on energy consumers are just as important or more important than direct effects. Activities such as irrigation, grain drying, seeding and harvesting are examples of climate dependent agricultural activities that have high energy uses. Transportation energy use is also affected by climatic variations. For example winter energy use by cars is lower in mild winters as compared to colder winters. He emphasized the lack of any work on these subjects at the time and the need for further investigation. No other Prairie work appears to have been done on this topic.

PAST CLIMATE VARIABILITY IMPACTS AS ANALOGUES FOR IMPACTS IN A WARMER FUTURE

Extreme years or sets of years provide good "experiments" to assess the sensitivity of sectors to climate. A few of these have been done for energy. For example, energy and climate variations for the 1960 to 1989 period were presented by Wilson (1990) for the Saskatchewan Climate Advisory Workshop. He focused on power consumption and sources as affected by climatic variability. Time series of heating and cooling degree-days, energy requirements, peak load, electric heat load, air conditioning load, irrigation load, hydro generation, fuel costs and reservoir levels were provided. However, relationships of climate with loads and generation types were not developed.

The time series of heating and cooling degree-days (Figure 2) warrant further analysis. Although there is considerable year to year variability over the 1960 to 1989 period, the overall trends of decreasing heating degree-days and increasing cooling degree-days are evident. The greater variability of the 1980s as compared to the 1970s is also noticeable. The extreme high cooling degree-days accumulated in 1961, 1984 and 1988. The extreme low values for heating degree-days occurred in 1987, 1981 and in 1976.

Figure 2 Time series (1960 to 1989) of annual heating and cooling degree-days, Regina and Saskatoon, Saskatchewan



Source: (Wilson 1990)

Another example is the assessment of the environmental and economic impacts of the 1988 drought on the energy sector (Wheaton and Arthur 1989, Goos 1989). The decade of the 1980s brought several severe droughts that are thought to provide useful cases to test the climatic sensitivities of the environment and economy. The 1988 drought was the most severe for many Prairie regions and a few reports documented the effects. A warmer climate is expected to bring more frequent and severe droughts to the Canadian Prairies (e.g. Williams et al. 1988), so it is appropriate to consider these effects.

The environmental and economic impacts of the 1988 drought, with an emphasis on Manitoba and Saskatchewan, were documented by Wheaton and Arthur (1989; summarized in Wheaton et al. 1992 Climatological Bulletin). The highlights are:

Manitoba:

- hydroelectric power comprised 94 percent of all power generation in 1988, down 4 percent from "normal" years.
- a net expense of $18.5 million was accumulated by Manitoba Hydro by the end of the 1987 to 1988 fiscal year. Drought was considered to be the major contributing factor.
- costs of increased fossil fuel consumption and power purchases from other sources was almost half of the increase in expenses (before finance charges).
- hydroelectric generation dropped from a record 24 billion kWh in 1986/87 to only 18 billion kWh in 1987/88; and it dropped further to 15.2 billion in 1988/89 (a 36.7 percent drop between 1986 and 1988).
- export sales dropped to $31 million in 1988/89; a 72.6 percent drop from 1986/87.
- revenue from Manitoba customers increased from $508 million in 1987/88 to $569 million in 1988/89.
- a net income loss of $26.4 million was registered.
- reserves dropped from the 1986/87 high of $137.3 million to $92.4 million in 1988/89.

Saskatchewan:

- the proportion of thermal generation and the volume of energy imports increased due to the drought's effects.
- fuel, water and purchased electricity costs increased in 1988 by 28.9 percent from 1987, mostly because of the decline in hydroelectric generation and an increase in total system energy requirements.
- net income before finance charges increased 13.8 percent from 1987.
- operational problems were encountered at two of the thermal power stations. Low water levels, reduced water quality and high temperatures of the cooling reservoir water required reductions in generation capacity.
- hydropower was 37.5 percent below normal in 1988.
- electrical energy was imported to meet demands.
- SaskPower revenues from gas declined 2.6 percent from 1987 to $298 million in 1988. This decline was mainly a result of the warm winter.
- Saskoil's (now know as Wascana Energy Inc.) production of crude oil was apparently not adversely affected and increased 16 percent from 1987 to 1988.

Albertan energy implications of the 1988 drought were assessed by Acres International and summarized by Goos (1989). Electricity and natural gas usage was larger in 1988 than in any other year on record. It was expected that natural gas usage, for example, should have decreased because of the relatively warm winter in 1988. However, other factors, such as economic growth, were thought to have masked the sensitivities to climate.

The drought did not seem to cause the extensive adverse impacts for the energy sector in Saskatchewan and Alberta as it did in Manitoba. Manitoba energy production is more sensitive to drought because of its reliance on hydroelectric production.

ADAPTATION TO CLIMATIC VARIATIONS

Considering that such little published work is available for the energy sector, few adaptation strategies have been developed or evaluated. Adaptive strategies that are useful for dealing with the current climate are a start. Comprehensive testing of the effectiveness of adaptive strategies will require improved quantification of climate and energy interactions and of adaptive methods. This will allow researchers to model how well the adaptive responses work to decrease negative impacts and increase positive impacts. Table 2 summarizes possible impacts due to climatic change on various energy sectors.

Raban (1991) provides a comprehensive list of actions Manitoba Hydro uses as part of their normal practice that will help accommodate climatic change. Research into the various implications of climatic change is part of their adaptive approach:

- an emphasis is being placed on the physical, as well as the statistical, method of calculating probable maximum precipitation.
- planners have re-examined the long range load forecast. They calculated the change in load with different climatic change scenarios for median and extreme cases. The load shift from winter to summer resulted in increases in dependable energy.
- system expansion planning was also examined in light of climatic change. Results indicated that thermal plants become more suitable with increased warming, but hydro plants remain more economic, in general.
- improved capability to model the effects of icing on conductors. Weather stations are used to detect line icing conditions. This type of monitoring will be required to a greater extent with climatic warming.
- evaporative loss will become an increasing problem with climatic change. Research into improved methods of calculating evaporative demands is being sponsored.
- criteria for firmness of energy supply are being examined. Severe droughts, such as the 1987-1990 event are critical from an operating perspective.
- ice booms are being installed and tested. This type of work will become even more critical with increasing climatic change.

Raban also asks "What else could we be doing?":

- develop a contingency plan for demand side management in the event of energy shortages.
- cooperation with other agencies to increase and to improve the amount of climatic change related information received and shared.
- allocate resources for in-house experts to evaluate the probable effects of the most likely climatic change scenarios on the drainage basins.

CONCLUSIONS

Much of the policy and research work has emphasized direct climatic effects on electricity production, but the work must be broadened to include indirect effects and effects on other types of energy production , for example.

As the very small number of publications indicates, research regarding the climatic change and energy relationship in the Canadian Prairies is lacking. This is a constraint to the further assessment of the effects of future climatic change on the energy sector.

The literature has focused on only a few places in the Prairies and does not cover the area evenly. Saskatchewan and Manitoba appear to have been the primary focus of this limited work.

Table 2. Summary of possible climatic impacts on energy sectors

Sector	Climatic Change	Impacts	Reference[a]	Confidence in Sensitivity	Comments/ Region
Energy Demand	Increased temperature	Increased air conditioning and decreased heating Decreased winter transportation fuel and block heater demands	Various, e.g. Hengeveld 1991, Raban 1991	High	
	Decreased wind	Heating effects	IPCC WGII 1996		
	Humidity and cloud changes	Space conditioning effects	IPCC WGII 1996		
Energy Conversion	Increased temperature	Slightly less efficient thermal efficiency	IPCC WGII 1996	High	
	Changes in water availability	Cooling water quantity and quality	after IPCC WGII 1996		Supply constraints may be offset by spring runoff and severe summer storms depending on storage availability
Energy Transport and Transmission	Increased temperature	Pipelines and other infrastructure over permafrost are vulnerable Lower capacity of power lines	IPCC WGII 1996	High	
	Increased freezing rain	Power line icing	IPCC WGII 1996		
	Increased frequency and severity of storms	Effects on power lines- interrupted energy transmission	IPCC WGII 1996, 1990		
Coal Industry	Long term decrease in glacier runoff, decrease in summer soil moisture Decreased or changed river flow	Decreased hydropower production Increased demands for thermal production Increased demand and use for coal	Demuth 1996, Wheaton et al. 1992 (Drought analogue)		
Renewables- Hydroelectricity	Increased temperature Glacier retreat will increase streamflow initially, with long-term	Changes in production capacity Changes in timing of water supply, with less dependable timing.	IPCC WGII 1996, Demuth 1996, Wittrock 1992	Medium	

Sector	Climatic Change	Impacts	Reference[a]	Confidence in Sensitivity	Comments/ Region
	decreases				
Solar Energy	Changes in cloud cover and storms	Changes in production capacity	IPCC WGII 1996	Low	Wind and solar energy systems would be especially vulnerable to changes in extreme events (IPCC WGII 1996)
Wind Energy	Changes in storms, wind regime, e.g. speeds, direction, and timing.	Operational hazards	IPCC WGII 1996	Medium	
Biomass Energy	Reduced soil moisture and increased season length Increased frequency and severity of severe storms	Reduced and/or increased variability of biomass supply Change in crop types	IPCC WGII 1996	Medium	
Energy Extraction	Increased temperature-increased permafrost melting Reduced soil moisture, longer seasons	Infrastructure problems with melting permafrost	IPCC WGII 1996	High	
Pollution Control	Increased temperature	Increased surface level 0_3 formation and increased control needs	IPCC WGII 1996	Medium	

[a]with additions by the authors

ENERGY UTILIZATION

Energy utilization on the Prairies is dictated by a number of factors. These factors include the climate of the area, population density, distances for both personal and freight movement and the nature of commerce. Table 3 shows secondary (i.e. electricity rather than coal or water and refined product rather than crude oil) energy demand in the three provinces. This chapter is not intended to provide more than an overview, but energy consumption can be charted to show the impacts of, for example, cold weather or a prolonged cold spell (as discussed above).

Table 3. Secondary final energy demand 1995

Province	Electricity	Natural Gas	RPP	Renewable
Alberta	16%	50%	34%	n/a
	171.8 PJ	536.2 PJ	362.2 PJ	
Saskatchewan	13.5%	52%	32%	2.4%*
	52.4 PJ	202.7 PJ	124.4 PJ	9.5 PJ
Manitoba	23%	38.7%	38.3%	n/a
	57.9 PJ	97.5 PJ	96.4 PJ	

Source: Statistics Canada, Quarterly Report on Energy Supply & Demand
*Source: Saskatchewan Energy and Mines, Energy 2020
PJ = Petajoules = 1015 joules
RPP = Refined Petroleum Products

The Prairies are characterized by cold winters and hot summers with the associated need for effective space conditioning of buildings. Because of the need for comfort in both work and living accommodation, buildings tend to be constructed to be relatively energy efficient. This does not mean that improvements are not possible or desirable, rather that the starting point for efficiency is generally higher than in other parts of Canada.

The population of the Prairies is relatively low and dispersed across a large geographic area. The result of this is that transportation is a major consumer of energy.

The Prairies produce a substantial volume of primary product for processing elsewhere. This primary product includes agricultural and forestry materials, energy products (coal, oil and natural gas) and a variety of mining products of which potash dominates from a weight and volume perspective. Oil and natural gas are moved primarily by pipeline, although trucks are used to collect crude oil from wells producing small volumes and to move it to collection points, whereas the dominant mode for the solid products is rail (road transport plays a significant role in moving products, particularly agricultural, to rail transshipment points). With the geographic area of the Prairies and the distance to population centres or transshipment points for water transport, substantial amounts of energy are required to move these products.

The energy required for transportation must be added to the energy required to produce products in the first place. By way of illustration, agricultural products require the use of direct and indirect on-farm energy. Direct energy use includes the refined petroleum products to run farm equipment and indirect includes the energy required to manufacture farm inputs (fertilizer, herbicides and pesticides) and deliver them to the farm site. Extraction and initial processing of other primary products tend also to be energy intensive, this is particularly true of heavy oil and bitumen, which must be extracted using energy and then upgraded prior to undergoing the normal refining process to create the products seen at the retail level. Heavy oil or bitumen must be removed from the rock in which it is trapped. Some heavy oil will flow to the producing well, but recovery is not very efficient. Typically heat is applied to the oil to reduce its viscosity and improve the recovery efficiency. In the case of the surface minable bitumen deposits of the Fort McMurray area of Alberta, the sand is mined, the bitumen removed and the sand returned for backfilling. Upgrading the oil requires the application of heat to break the long-chain hydrocarbons to create a synthetic light crude that can be processed by a standard refinery. Frequently, hydrogen (from natural gas) will be added to the crude to increase the process efficiency.

By way of example - the energy utilization in Saskatchewan can be broken out by use in Table 4. The other two provinces will have similar distributions.

Table 4. Energy Demand by Sector in Saskatchewan, 1995

Sector	Residential	Commercial	Industrial	Transport	Pipelines
PJ	61.85	42.02	189.47	117.22	54.31
Percentage	13.3%	9.0%	40.8%	25.2%	11.7%

Source: Statistics Canada, Quarterly Report on Energy Supply and Demand

PJ = Petajoules = 10^{15} joules

When considering energy from the perspective of adapting to climate induced change, one of the more important aspects is a discussion of the distribution networks. As indicated above, on the Prairies the primary sources of electricity are determined by the geological and geographic availability of the primary energy sources, coal or adequate dam building sites. While the supply is, of necessity, concentrated in large point sources, the distributed nature of the population and industry dictates that an extensive distribution network is required. Much of this network carries low or relatively low loads.

The same discussion is also true of natural gas distribution systems. Although the sources of natural gas are more widespread in Alberta and Saskatchewan, much of the network of distribution lines carries relatively low volumes. The nature of the distribution network makes it relatively expensive to operate on a per unit of energy basis when compared to an area of dense population with a concentration of industry. Even refined petroleum products require a substantial network of retail outlets with low volume sales.

IMPACTS OF CLIMATE CHANGE ON ENERGY

The science of climatic change has undergone much progress since the initial Intergovernmental Panel on Climate Change assessment (IPCC 1990). Global warming and other climatic changes are forecast to continue into the future based on current and forecast growth of greenhouse gas concentrations in the atmosphere. The annual to decadal changes would include considerable variation, but the average rate of warming would likely be greater than any seen in the last 10,000 years. Temperatures are projected to continue to increase beyond 2100, even if concentrations of greenhouse gases were to be stabilized by that time (IPCC WGI 1996).

Confidence in estimations of future possible climates at the regional scale remains much lower than at the global or continental scale. Also estimates for temperature have higher confidence than estimates for other impacts such as precipitation and soil moisture. However, large changes in the frequency of extreme events are known to occur with small changes in mean values of climatic elements. Climate models (GCMs) agree on the following future climate changes (IPCC 1996WGI: 42-44):

- maximum warming in high northern latitudes in late fall and winter (related to reduced sea ice and snow cover);
- reduced diurnal variation over land in most seasons and regions (greater increases in night than in day time temperatures);
- enhanced global mean hydrological cycle;
- increased precipition in high latitudes in winter;
- increased soil moisture in high northern latitudes in winter; and
- increased number of extremely high temperature events and decreased number of extremely low temperature events.

While the physical changes that could occur on the Prairies as a result of Climate Change are speculative at this point in time, due in part to the scientific uncertainties and in part to the difficulties of relating these changes to the regional level, it is important to understand the impacts of "probable" changes. Probable change refers to the likely regional outcome based on the IPCC predictions of change that would occur in a mid- to high-latitude region with a continental climate.

In basic terms, these projected changes could result in an increase in mean annual temperature of several degrees Celsius. The outcome of the temperature change would be a longer frost free period, more evaporation in the summer and fewer or shorter cold spells in the winter. Changing precipitation patterns would also be likely to occur; these are less predictable, but are likely to result in lower summer rainfall, even if total rainfall remains the same or increases as a result of an intensification of the global hydrological cycle. In addition to changes on the plains, all three provinces would be impacted by changing temperature and precipitation patterns in the mountains - the source of water for the major prairie rivers.

These changes will have a number of direct and indirect impacts on energy production, distribution and use. Some of the major implications are outlined below:

- Higher mean temperatures will create a reduced winter heating load and the potential for increased summer cooling load.
- Surface waters are likely to be warmer and the increased evaporation result in reduced volumes and water quality.
- There is likely to be an increased demand for water to meet domestic, industrial and agricultural requirements.
- Changes to soil water availability could result in changing land use, particularly in marginal areas, and the demographic changes that would be required to accommodate changed land use.

Oil production over much of the Prairies will increasingly rely on the availability of water, either for waterflooding or for the production of steam for thermal recovery of heavy oil and bitumen. Water can be pumped into the reservoir as a liquid to assist in pressure maintenance and to help push more oil to the producing well. In heavy oil and bitumen deposits where surface mining is impractical and waterflooding has limited application because of the nature of the oil, heat can be applied to the oil to make it move more freely. At present, the most effective means of applying the heat is to force steam into the reservoir. Where these procedures rely on deep subsurface water or processed produced water there should be little problem since there is no call to use water of such quality for domestic or agricultural use. Where they rely on the availability of near surface ground water or surface water, there is the potential for oilfield use to compete with other uses.

Natural gas distribution could be affected by the changes outlined above. Changing heating load could impact on a system that already has a marked seasonality to its utilization, although the impact might well be too small to affect the overall economics of the system. Changing demographics as other sectors of the economy adapt to new climatic and land use patterns on the Prairies could also impact the utilization of the existing infrastructure.

Electricity has the potential to be most severely impacted if climate change becomes a reality. At the production end, thermal power stations become less efficient [2] as surface water temperatures increase and, potentially, volumes decrease. This situation was displayed in 1988 when a number of coal-fired power stations were forced to operate at reduced capacity due to water supply and quality problems. Impacts of this severe drought are discussed in the literature review section, this chapter.

Reduced surface water could have an effect on hydroelectric production,[3] from simply having less water available to competition for the same water from a number of other uses, primarily agricultural. Increased demand for water pumping and summer cooling and a decreased winter demand could push electrical utilities into a summer peak load position. As with natural gas distribution, changing demographics could have effects on the utilization of existing infrastructure.

From the perspective of electrical power production, it is important to note that a substantial amount of the water utilized comes from rivers that have their water sources in the mountains. Understanding the impacts of changing snowfall and snowmelt patterns will therefore be necessary. Changing climate, both

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[2] Thermal power stations rely on cooling water to condense the steam used for operating the turbines at the end of the cycle. Warm intake water reduces the efficiency of this process, which, in turn, reduces the capacity at which the unit can operate.

[3] In Saskatchewan, the water for hydroelectricity is stored behind dams. Reduced inflow to the dams can substantially impact the capacity to produce electricity. In Manitoba, much of the hydroelectric capacity is run-of-river with some storage in lakes (primarily Lake Winnipeg) or behind dams. Reduced flow, more marked seasonal flow patterns or lowered lake levels can all impact production capacity or timing of capacity availability.

precipitation and temperature, will impact on glacier characteristics. The National Hydrology Research Institute has been working on the effect of glacier variations on stream hydrology (e.g. Demuth 1996). In the longer term, the impacts on river flow could be marked (discussed more fully above). In addition, there are in place regulations around water use and release in the three Prairie provinces to ensure the health of the river systems.

Renewable energy is not immune to climate change on the Prairies, although the impacts are far less clear. Changing temperatures, season length and moisture regimes could result in the production of different crops in the agricultural sector; this may or may not have an effect on the potential of agricultural biomass for renewable energy production. Similarly, the longer term impacts on the forestry sector are not well understood. Increased environmental stress, particularly at the southern margins of the boreal forest, would have a negative impact on the availability and productivity of biomass, at least from the southern areas. Year round availability of solar energy might be affected by seasonal changes to precipitation or increased cloud cover if evaporation increases globally. Wind regimes will likely change; whether the effects would be positive or negative remain to be determined. Currently there is little consensus among models regarding the expected changes in storminess and associated extreme wind speeds (IPCC WGI 1996).

ADAPTATION

As discussed above, the energy sector has been thought of largely as an area for mitigative activities. Certainly the production and use of fossil fuels creates the majority of greenhouse gas production on the Prairies and activities in energy efficiency and conservation are promoted as the primary means to combat the potential effects of climate change. It should also be noted that growing greenhouse gas emissions in the developing economies, particularly southeast Asia, and future growth in the transitional economies means that emissions will continue to grow regardless of mitigative activities from the Prairie energy sector.

Based on the above tenet, it will be important for the Prairies to evaluate what the physical effects of climate change might be and the results of these changes to life and commerce. Adaptation to climate change will occur whether or not the decision is made consciously. The risk of taking a reactive response to change is the inability to take full advantage of that change and potentially allowing the economy to suffer from the ensuing socioeconomic problems. Climate change has the potential to alter land use patterns on the Prairies with the associated changes to habitation patterns. Understanding the impacts will allow the Prairies to take advantage of the positive aspects of change and minimize the negative consequences, particularly as they relate to the energy sector.

From an energy perspective, therefore, it will be necessary for energy decision makers and planners to understand not only the direct impacts of change on energy production and distribution functions, but also the effect on energy demand and distribution of the numerous adaptive strategies that will be implemented by other sectors of the economy. In other words, understanding the decisions made by energy users as they adapt to change will be important to energy planning.

RESEARCH AND POLICY

As stated previously, the research undertaken and literature published on the subject of climate and energy interactions (especially climatic change aspects) in the Prairies is sparse. Therefore, recommendations tend to be very general. In addition, since the focus of attention has tended to be the electrical sector, a broadening of prairie work is required.

Research on each topic presented in Table 2 regarding possible impacts should be considered. It has been assumed that the energy sector is most sensitive to space conditioning loads (e.g. IPCC WGII 1996). However, an overview sensitivity analysis has not been performed. Such work would confirm assumptions specific to the study area and would also be very useful for priority setting. Following are examples of questions extracted from the literature:

- What are the sensitivities of different parts of the energy sector to climatic change?

How do these compare to the sensitivities of other sectors?
- What are the effects of droughts and floods on the energy sector. What implications would the findings have for future effects and adaptations in a changing climate?
- What is the extent of knowledge of indirect effects - e.g. with changing residential demand (e.g. space conditioning), can the industrial demand be met?
- What are the best quantitative and qualitative models for use in estimating impacts and testing adaptive strategies?
- What are the interactive effects of climate change and how does this affect adaptation? For example, energy loads are affected by agricultural energy use demands. Agricultural energy uses are sensitive to climate, especially extremes (Hengeveld 1991).
- It is often assumed that climatic change will occur gradually, which would make adaptation easier. There is, however, some indication that climate has undergone large changes in decades or less. How would the rate of change affect impacts and adaptation?

With regards to policy, the following questions are raised:
- How adequate are current policies and practices in responding to changing climate? (e.g Raban 1991).
- What infrastructure effects can be expected? For example how will continued permafrost thawing affect pipelines and other energy related infrastructure?
- What is the balance between adequate adaptation and mitigation? What are the linkages between adaptation and mitigation? For example, how will mitigation policies affect the capability to adapt? (IPCC WGII 1996).

Based on the above analysis and general questions gleaned from the current literature, research and the associated policy analysis should specifically reflect the following priorities:
- There is a need to monitor and to assess the timing and risk of climate variation and change occurring globally and in the three Prairie provinces.
- Once the risk is understood, the likely impacts of change on agriculture, water supply, forestry, transportation and other sectors can be assessed.
- These changes will have a direct impact on the energy production and distribution industry. Depending on the nature and assessed risk of these changes, a preparation and response strategy can be developed by industry to accommodate future changes.
- An aggregation of the adaptive strategies of the other sectors of the economy will provide an insight into the likely demographic and industrial changes that will occur. This would provide an understanding of areas of competition for resources, particularly water, and where the energy will be required.

It should be noted that one of the adaptive strategies that could be employed by industry and individuals is mitigation through actions to reduce fossil energy consumption. This, in itself, will result in the need for the energy sector to adapt to changes in energy demand.

Major energy projects can take many years of planning and construction and are intended to be in operation for a number of decades. For example, a major power plant can take up to a decade in the planning, construction and commissioning stages and have a life expectancy of 35 years. Life extension can extend plant life by a couple of decades. Major facilities would, therefore, be in operation during a period of time when forecasting models tell us we can expect to see change on the Prairies and adaptation to occur in other sectors of the economy. We could, in effect, have energy supply sources in place that are overbuilt relative to calls on various energy forms, this should have some bearing on the size of unit additions called for in the energy sectors' attempt to closely balance supply with forecast energy demands.

This paper has focused on change in climate and the impacts on the energy sector directly and through the clients it serves. Change includes changes to what we consider to be the "normal" climatic conditions (mean annual temperatures, precipitation levels, number of frost free days, etc.) as well as changes to the variability and extreme events that occurs annually or over a period of years. Extreme events can have an impact on the energy sector and the client group it serves. Understanding the nature of these extreme events, their likely occurrence and the sensitivity of various sectors to this type of variability becomes an important planning tool. Any study of climate change must, therefore, include the climatic variability that is also affected by change.

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APPENDIX: ENERGY PRODUCTION

The Prairies are fortunate to have access to a broad range of energy resources. These resources include fossil fuels (coal, conventional and non-conventional oil resources and natural gas), uranium (not used to generate energy on the Prairies), hydropower and the potential for non-hydraulic, renewable energy sources (including wind, solar, ethanol, wood waste and geothermal). Since uranium is not used as an energy source, it is considered as a commodity only and will, therefore not be discussed extensively, despite its economic importance.

Currently, the energy produced on the Prairies is dominated by fossil fuel production. Oil is produced in all three provinces, natural gas and coal are produced in Alberta and Saskatchewan. The following table (Table A.1) provides the annual production volumes of the three fuel types.[4]

Coal is widely distributed across Alberta and Saskatchewan, with the grade generally increasing in a westerly direction. Lignite is mined in southeastern Saskatchewan, sub-bituminous coals on the plains in Alberta and sub-bituminous to bituminous coals in the foothills of Alberta. A substantial amount of the coal is utilized for mine-mouth electrical generation, the rest is sent by rail to either Ontario for electrical generation or to the west coast for export. A small amount of coal is used for domestic or institutional heating or for the manufacture of charcoal briquettes. Most Prairie coal is mined using the open-pit method. These shallow, low-grade coals contain little methane, so mining related emission of this greenhouse gas is minimal. The following Table (A.2) gives the volumes of coal mined and its utilization for the two provinces.

Oil is produced in southwestern Manitoba, in southern and west central Saskatchewan and across much of Alberta. The oil quality varies considerably from light sweet crudes to the immobile bitumens of northern Alberta. Refineries and upgraders in Alberta and Saskatchewan process some of the produced oil. The majority of the oil, including most of the upgraded heavy oil and bitumen, is moved by pipeline to refineries in central Canada (with the reversal of the Montreal-Sarnia pipeline, only Ontario will now receive western crudes) and the United States or across the Mountains to the west coast (Vancouver and northern Washington State). Table A.3 gives the volumes of oil produced and exported from the Prairies.

Natural gas is produced primarily in Alberta and along the western border of Saskatchewan. This gas is used domestically or exported. Most of the exported gas is moved to central Canada and into the United States; there is some movement into British Columbia. Table A.4 gives the volumes of gas produced and moved out of the Prairies.

Natural gas can be distributed directly to end-users as an energy source. Crude oil is processed to create refined petroleum products and distributed in this form. Coal, however, is generally converted to electricity, a secondary form of energy, before use. The same is true of hydraulic energy. On the Prairies, the vast majority of electricity is generated by coal combustion or hydraulically, a small amount is produced by natural gas combustion. (Wood waste, wind and diesel fuel are also used to produce electricity, but in niche circumstances only.)

As a result of the cost of developing the necessary infrastructure for the production of electricity, large central facilities have tended to be the norm. The locations of these facilities are geographically determined by availability of the primary resource, the locality of the coal mine or the suitability of the site for a dam or for run-of-river production[5]. To

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[4] The calculation of reserves, or the resource available for future production, is important for non-renewable resources. For the purpose of this study, however, it is assumed that fossil fuel production and use will continue to be important to the economy for the foreseeable future.

[5] For the purposes of this study, the hydraulic generation capacity of the Prairies is considered as a conventional source of electricity rather than renewable. These smaller units are generally run-of-river; ie, no dam is required and generation capacity depends on the flow in the river at any time.

utilize coal, not only must the power plant be constructed, but the coal mine, or mines, must be built. To achieve economies in mining, the scale must be relatively large. Few hydro-electricity sites in the Prairie provinces are "run-of-river" where a dam is not required to create the necessary hydraulic head and to store water from the spring run-off. Historically, it has been more economical to produce electricity from large facilities (with coal or water as the energy sources of choice) because of the fuel cost and availability. Table A.5 shows the percentage of electricity generated by different energy sources in the three provinces.

Table A.1 Prairie fossil fuel production - 1995

Province	Coal (million tonnes)	Oil (million m^3)	Natural Gas (billion m^3)
Alberta	37.1	88.3	161.1
Saskatchewan	10.7	18.8	8.7
Manitoba	n/a	0.6	n/a

Source: Saskatchewan Energy and Mines, Mineral Statistics Yearbook
Manitoba Energy and Mines, Alberta Energy
Statistics Canada
*Includes all gas (flared, losses, adjustments, etc)

Table A.2 Coal production and utilization - 1995

Province	Total Produced (million tonnes)	Mine Mouth Generation (million tonnes)	Export from Prairies (million tonnes)	Miscellaneous
Alberta	37.1	25.6	11.5	minor
Saskatchewan	10.7	9.4	1.3	minor

Source: Saskatchewan Energy & Mines, Mineral Statistics Yearbook
Alberta Energy

Table A.3 Oil production and utilization - 1995

Province	Total Produced (million m^3)	Synthetic Production (million m^3)	Exported to US (million m^3)	Exported to other parts of Canada (million m^3)	Total Utilized as RPP* (million m^3)
Alberta	88.3	16.2	45.2	23.6	13.2
Saskatchewan	18.8	n/a	11.7	3.4 million tonnes	3.7 million tonnes
Manitoba	0.6	n/a	0.4	0.2	2.7

Source: Saskatchewan Energy and Mines, Mineral Statistics Yearbook
Manitoba Energy and Mines
Statistics Canada
* includes producer consumption and non-energy use

Table A.4 Natural gas production and utilization - 1995

Province	Total Produced (billion m^3)	Total Utilized* (billion m^3)	Exported to US (billion m^3)	Exported to other parts of Canada (billion m^3)
Alberta	162.1	62.8	67.2	32.1
Saskatchewan	8.7	4.74	0.52	3.45
Manitoba	n/a	n/a	n/a	n/a

* (Includes primary and producer consumption and all other losses)

N.B. - Saskatchewan imports some gas from Alberta for use allowing for greater exports of domestic production.

Source: Saskatchewan Energy and Mines, Mineral Statistics Yearbook
Alberta Energy

Table A.5 Electricity generation - 1995

Province	Coal (million kWh)	Hydraulic (million kWh)	Natural Gas (million kWh)	Import (net) (million kWh)	Other (million kWh)
Alberta	42 461	1 792	3 134	740*	14
Saskatchewan	12 669	4 137	119	291	---
Manitoba	125	29 013	14	---	85

Source: Manitoba Energy, SaskPower Annual Report (1995), Alberta Energy
* Total electrical imports to Alberta

Renewable energy sources offer potential for the future, but are generally regarded as uneconomic or impractical at the present time for a number of reasons discussed below. Forestry waste has potential and is being used to a small extent for the production of electricity and heat. Similarly, agricultural waste has potential, but transport, storage and the loss of organic matter to the soil are all significant hurdles. Currently, the only moderately extensive use of agricultural product is the conversion to ethanol for use as a gasoline additive or replacement. Two conversion facilities are in operation, one has recently entered receivership and three are in the planning or financing stages.

Wind has been studied as a energy source, but is in use as a means of generating electricity on a small scale for the grid in Alberta only. It has a large potential as a source of electricity, but requires either cheap storage of energy or the availability of another energy source to provide backup during periods of low or no wind. Wind also has a niche market on the Prairies as a means of pumping or aerating water. Similarly, solar energy has niche, small-scale applications. The hurdles to solar as a source of electrical energy for the grid are currently too great to allow it to be a viable alternative. These hurdles include capital cost and the provision of backup power or cheap storage of energy.

For completeness, the potential for geothermal energy should be mentioned. Across the plains portion of the Prairie provinces the geothermal gradient is generally low making geothermal energy a low grade energy source with potential only for space heating. Higher gradients in the mountains might offer more potential in the future, again primarily as a heat source.

Electricity could also be produced from nuclear energy in the future. Nuclear energy is used extensively in Ontario where there is a large electrical demand and alternatives such as coal, oil or natural gas all have to be imported. The price of traditional energy forms on the Prairies and the requirement to add generation capacity in smaller increments than has been typical for nuclear energy has resulted in uranium being viewed as a fuel with potential for future use, rather than as a current competitor for traditional fuels. The design of smaller generation and heating units is changing this perception of the competitiveness of nuclear power.

APPENDIX D

THE INSURANCE INDUSTRY AND CLIMATE CHANGE ON THE PRAIRIES: A STATUS REPORT

THE INSURANCE INDUSTRY AND CLIMATE CHANGE ON THE PRAIRIES: A STATUS REPORT

Marion Meyer
International Institute for Sustainable Development
Winnipeg, Manitoba

EXECUTIVE SUMMARY

The purpose of insurance is to reimburse individuals for losses on property, health, crops, life etc. Insurance can generally be defined as provision against catastrophe and is the pooling of risk. Climate change poses a unique problem in the assessment of risk for the insurance industry. Characteristically the assessment of risk has been based on the assumption that events in the past adequately reflect what can be expected in the future. Climatologists are not convinced that the results of climate change can be predicted with any certainty and are of the opinion that calculations of climate change related risk should be based on expectations of the future not the past. In this regard, good scientific knowledge, in combination with engineering and financial analysis techniques are necessary.

General circulation models (GCMs) - which look to the future - imply warmer temperatures and decreased soil moisture with a doubling of the concentration of atmospheric carbon dioxide for the prairie region. With a greater expected frequency of climate related disasters on the prairies such as hail damage to crops and property, or crop failure due to drought, pests or storms, as well as direct and indirect health effects (like an increased incidence of allergy disorders) demand for insurance will increase. This demand for insurance will only be met if the global insurance market has the capacity to underwrite all the risk. Thus, insurance in the prairie region is not only affected by local events but also by climate catastrophes in the rest of the world which also impact on the health of the industry as a whole. Insurance companies both in the prairies and across the globe will attempt to reduce their losses - and thus increase their capacity to underwrite risk - by increasing premiums, withdrawing coverage altogether, or by making the underwriting of risk conditional on certain actions being taken by the policy holder. If climate catastrophes were to escalate to the degree that the global insurance industry were to collapse it would have ramifications for individuals, the economy as a whole and financial markets too. Individuals would have to bear the entire financial burden of recovery, local economies would take longer to recover than usual and world financial markets would collapse since insurance companies invest heavily in them.

In light of the above, the author has made the following recommendations for further research and analysis:

- Understanding of climate variables and how they interact to influence weather and climate in the prairies needs to be deepened,
- More study needs to be done on the kinds of risk that insurance companies can expect to incur when covering climate related damages in the prairies,
- The links between scientific, financial and statistical analyses and the use of remote sensing and other techniques need to be developed in order for insurance companies to accurately assess their risk and project future losses, and
- The possible effects of climate change on the health of individuals in the prairies needs to be thought through.

INTRODUCTION

"Climate change could bankrupt the industry"
(Frank Nutter, President of the Reinsurance Association of America in (Nutter, 1996))

The insurance sector will be affected both by natural disasters and health concerns resulting from climate change. Weather and climate change are of interest to the insurance industry because they inflict damage on people's property, crops, or health. Through the pooling of funds, insurance companies are able to help individuals and commercial companies recover from their losses. This is especially important where the losses are too great to be absorbed by these individuals and companies.

The insurance industry is in the business of risk and works in the realm of uncertainty. Insurance companies attempt to quantify the probability that an uncertain event (like a tornado) will occur. Hence, risk is uncertainty quantified. Since the insurance industry has experience in quantifying uncertainty, it is not unduly challenged by the fact that climate change is uncertain. Rather, the industry is concerned with how the frequency of extreme weather events might change as a result of climate change, as well as the degree of damage that will result. Risk associated with climate change has to be assessed differently from the way in which the industry characteristically does this. Currently past occurrences of an event such as a flood have been used to help assess the risk of this same event happening in the future. The insurance industry can no longer assess risk based on past experience but has to look to expectations of the future. Comprehensive and accurate scientific knowledge is necessary if the insurance industry is to assess risk related to climate change and variability reliably.

Climate change is a global phenomenon and insurance is a global, as well as a local, market service. Therefore, the effects of climate change on the prairies on the insurance industry cannot be looked at in isolation of the rest of the market and the world. This paper is a literature review of papers, articles and newspaper clippings relating to climate change and the insurance industry in general with some application to the situation on the Canadian prairies. So far very little has been written pertaining specifically to the prairie case. In light of this fact, the author has concluded with some recommendations that could shed more light on this topic.

INSURANCE: HOW IT WORKS

The sole purpose of insurance is to reimburse the insured for losses on property, health, crops, life etc. Insurance can generally be defined as provision against loss[1] i.e. in the event that the system is no longer able to handle the loss by its own means. Insurance is the pooling of risk in order to spread the losses of a few (individuals/companies). A number of individuals contribute financially to a pool of funds that can be used to reimburse the contributors for damages incurred. The idea of insurance is based on the assumption that the risk that all contributors will incur damages at the same time is low. In other words, each contributor helps the other contributor to recover financially from a loss that they would otherwise be unable to cope with individually. This principle can only work if the insured risks of the individual members of the insured community are similar. The insurance industry maintains equity of risk by setting premiums accordingly (Baker, pers. com.; Greenpeace, 1996; Swiss Re, 1994).

The insurance sector consists of three main players: policy holders (the insured), primary insurers (insurance companies), and re-insurers (the insurance companies that insure the primary insurers). The interaction of these three players can be observed in diagram 1. Policy holders are confronted with the possibility of a loss (a tornado for example) and they approach a primary insurer to spread their risk of this happening for them. The primary insurer agrees as long as the policy holder is willing to pay the premium. This premium is set based on the insurance company's assessment of the risk that a tornado will actually take place, as well as the eventuality that the policy holder will be unable to cover the loss themselves. The higher the risk, the higher the premium. The primary insurer also takes out insurance against the possibility of its policy holders claiming a loss by paying a premium to a reinsurance company. The reinsurance company also sets its premiums based on the risk it expects is associated with the primary insurers claiming losses[2]. When a policy holder claims a loss from a primary insurer, who consequently claims from the reinsurance company, the policy holder's premium is recalculated (in accordance with the terms of the policy) based on the new information and a new estimation of risk.

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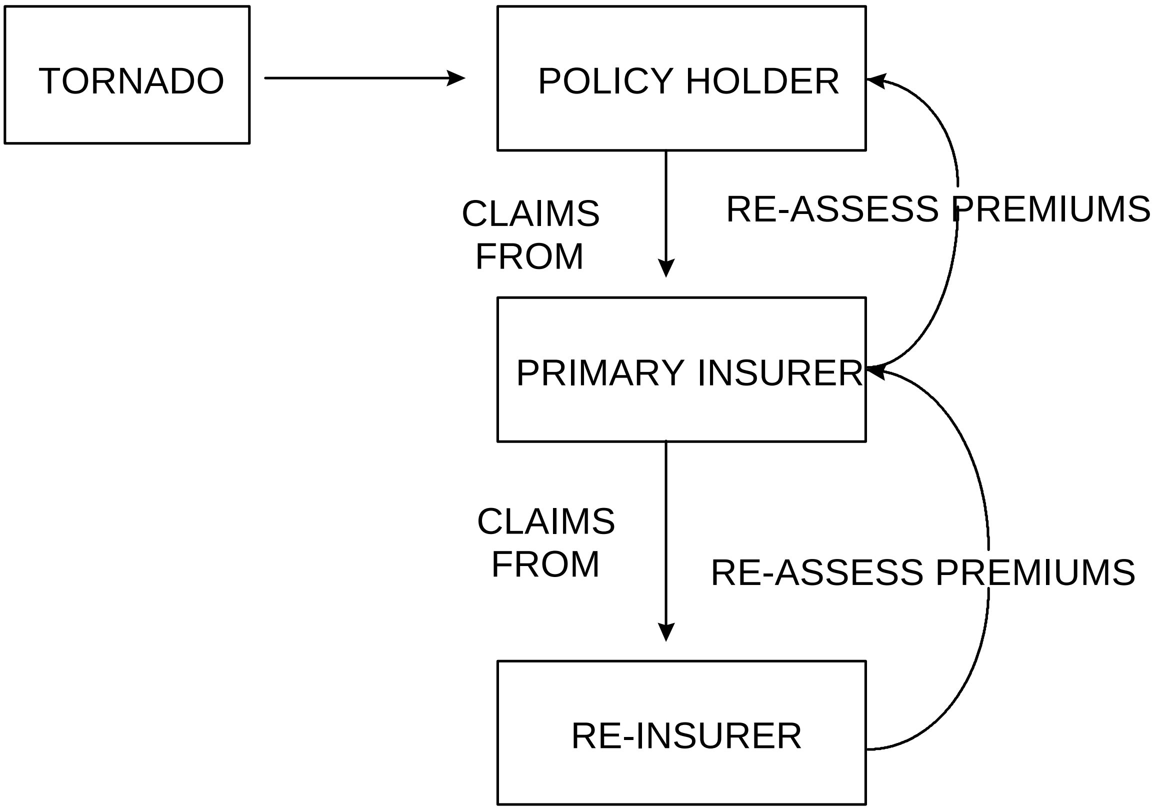
[1] Insurance effectively converts a loss into an expense consisting of a deductible and a premium. Hence, insurance is provision against any loss exceeding the deductible (Baker, pers. com.).

[2] At times re-insurers re-insure their own risk through a retrosessionaire, adding a fourth dimension to diagram 1.

Figure 1: Relationship amongst the three players in the insurance sector.



The degree of risk that insurance companies face is influenced by two factors: the probability that an event will occur (e.g. a tornado) which results in loss to the policy holder; and the probability that the policy holder will not be able to cover the economic loss associated with the event. Traditionally risk is calculated based on observations of the past. The more observations that have been made in the past the more accurate the calculation of the risk is. The accuracy of the risk calculation is also influenced by how well the interaction of all the variables is understood (Nutter, 1996; Swiss Re, 1994). Climate change poses a challenge to the insurance industry on both these fronts.

Weather is what happens locally at a given time, while climate is a statistical average of weather, usually made over a period of 30 years, though depending upon the application, this time period can be varied. Meteorologists are able to forecast the weather over the next couple of days with reasonable accuracy but are unable to make long range forecasts because of the chaotic nature of the atmosphere, as well as the number of variables that come into play[3]. For this reason, while climatologists have a specific idea of how the climate variables interplay, they are as yet unable to accurately predict the outcome. The results of climate change in the future are thus based on speculation rather than certainty. Weather records have also only been kept for too short a period of time to be able to say with any accuracy whether climate change is in fact occurring (Nutter, 1996; Swiss Re, 1994).

If climate is in fact changing (and insurance companies are considering it prudent to assume that it is (Nutter, 1996; UNEP I.I.I, 1996; Swiss Re, 1994; Leggett, 1993)) then assumptions about possible catastrophic weather events cannot be made based on past experience. So, insurance companies can no longer calculate risk based on historical data but should look to the future in

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[3] Variables include: precipitation levels, atmospheric winds, ocean currents, sea surface temperature, greenhouse gas concentration in the atmosphere as well as their radiative properties, among others.

calculating and mitigating risk. Good scientific knowledge, in combination with engineering and financial analysis techniques, is needed in this regard. Given that weather cannot be arbitrarily influenced by our actions either, the only possibility remaining in dealing with losses resulting from climate change is to reduce the scope of the damage. Insurance companies reduce the "scope" of their losses by increasing premiums and/or deductibles, reducing or withdrawing coverage altogether, or by making the underwriting of risk conditional on certain actions being taken by the policy holder (Nutter, 1996; Swiss Re, 1994; Deering, 1994). If catastrophic weather events become more frequent and possibly less predictable, insurance companies may be faced with no other choice but to withdraw coverage. This is especially true for policy holders who are located in vulnerable areas like coastal belts because sea levels are expected to rise and frequency and intensity of storms is expected to increase.

Globally, the insurance industry is dominated by four European and U.S. reinsurance companies. There are other reinsurance companies based in Australia and Japan but they do not play as large a role. The fact that the global reinsurance market is dominated by only four major companies is important for the industry as a whole regardless of where in the world primary insurers are located. The size of the global insurance market's financial loss reserve is currently (US) $160 billion a year. If the industry were to incur losses because of a hurricane in the Caribbean, mudslides in Mexico, and drought in the North American Great Plains simultaneously (i.e. in the same year), the chances are that the reserves would be depleted and the industry may not be able to cover all claims and could go bankrupt. Eugene Lecomte (in Deering, 1994), President of the Insurance Institute for Property Loss Reduction, states that two events could conceivably take away $70-80 billion of the $160 billion in surplus. If that happened, "you'd cripple the industry. It wouldn't be able to take on new risks. It wouldn't have the capacity to underwrite the future. We'd have massive, massive availability problems." This is the kind of risk that the industry may be facing if climate change is happening, and especially if it were to happen rapidly (Knox, 1996; Greenpeace, 1996; Deering, 1994; Flavin, 1994; Leggett, 1993).

CLIMATE CHANGE ON THE PRAIRIES AND ITS EFFECT ON THE INSURANCE INDUSTRY

Climate on the Prairies

The Canadian prairies consist of the Manitoba lowlands, the Saskatchewan plains and the Alberta high plains. The soils in this region are highly suited to agriculture. For this reason, the region plays a major role in agriculture in Canada and international trade. Close to 40% of the prairie provinces' economic activity consists of primary agricultural production, with a large majority of other economic activity comprising the provision of inputs for agriculture, or transporting, marketing, or processing agricultural products. Thus the prairie economies are vulnerable to climatic conditions because agriculture is extremely vulnerable to climatic conditions (Cohen et al., 1992).

Prairie climatic conditions have always been varied and to a degree unpredictable. At its extremes the prairie climate is characterised by droughts and dry spells, early and late frosts, cold spells, excessive moisture and flooding. It is a climate of extremes with minimum temperatures dropping below -400C in January and rising to a maximum of between 350C and 400C in July. Annual precipitation is between 250 and 450mm, with more than two thirds occurring during summer (May to August) months. Passages of cold fronts, depressions, and numerous storms generate strong winds throughout the year. Dust storms are frequent during drought years but have also been found to occur during relatively short lived dry conditions (Jones, 1996; Cohen et al., 1992).

General Circulation Model (GCMs)[4] scenarios for the prairie region all show an increase in temperature and reductions in soil moisture with a doubling of atmospheric carbon dioxide. Some models have shown an increase in precipitation and others have decreased precipitation. In both cases soil moisture is predicted to diminish due to high rates of evaporation over a longer period of time because of the large rises in temperature.

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[4] GCMs most commonly used in Canadian studies are Environment Canada's second generation CCC GCMII, Princeton University's Geophysical Fluid Dynamic Laboratory (GFDL) GCM and NASA's Goddard Institute for Space Studies (GISS) GCM. Scenarios created using GCMs are usually based on a doubling of atmospheric carbon dioxide (Taylor, 1996).

During a typical summer, the prairies lose more water through evaporation than falls as rain making the region extremely dependent on winter snowfall to replenish losses. Droughts could become more frequent and severe as a result of lower soil moisture levels and lower precipitation levels (be it snow or rain). The loss of soil organic matter compounded by drier conditions will also lead to an increase in dust storms (Jones, 1996; Fosse & Changnon, 1993; Cohen et al., 1992).

The effect on the insurance industry

As was mentioned above, the local insurance industry is part of a larger global market. So the insurance industry on the prairies will not only be affected by the effects of climate change within the region but also by climate catastrophes all over the world which will result in changes to their reinsurance rates and availability. As natural disasters such as windstorms, hailstorms and drought become more frequent and severe (as is conjectured), more and more policy holders on the prairies will be claiming from their insurance companies. If insurance companies have insufficient surplus funds to service the claims and insufficient insurance coverage of their own then they will go bankrupt. Smaller insurance companies are at greater risk of this happening. As smaller companies go under there will be fewer companies paying premiums to the re-insurers who are then able to underwrite less future risk of climate damage due to smaller reserves. In other words the industry as a whole becomes incapable of supporting more damage.

With a greater frequency of climate related disasters on the prairies such as hail damage to crops and property or crop failure due to drought, pests or storms, demand for insurance will increase. The 1988 drought is an example of this where demand for “rain insurance” in the northern Great Plains of the United States rose sharply as agricultural producers realised that it was going to be an unusually dry summer. This situation is also a good example of how insurance companies lost money - Federal Insurance Company lost $20 million and CHUBB Corporation lost $48 million in claims - because claims exceeded the amount that the insurance companies had been underwritten for (Changnon & Changnon, 1990). Despite rising demand for insurance which would result from an expectation on the part of individuals that climate change will lead to greater losses to property and crops, smaller insurance companies and policy holders may be unable to afford the higher premiums which will accompany the higher risk. Underwriters (re-insurers) may also be less willing to accept this risk (given that risk assessment relating to climate change is still in its infancy). Some companies may refuse to cover certain eventualities and others will increase the deductibles that policy holders have to bear before the insurance company will pay out a claim. In other words, the amount of insurance in comparison to the premium paid will decline (Fosse & Changnon, 1993). Crop insurance in the Canadian prairies is administered and supported by the three provincial governments. As such, producer premiums may increase, or taxpayers will be expected to carry the increased state expenditure on crop insurance. Alternatively, the increased expense may be shared by both the producer and the taxpayer.

An as yet little discussed sphere of insurance that could/will be affected by climate change is health and personal liability insurance. Direct health effects of climate change are anticipated to be increased mortality and illness due to expected increases in temperatures and duration of heat waves (Wheaton & Wittrock, 1992). Temperature induced death in colder regions should also lead to fewer cold-related deaths. Indirect health effects would be aggravated respiratory and allergic disorders spurred on by dust storms, the presence of air pollutants, pollens and moulds. Cancers (such as skin cancer) associated with ozone depletion and indirectly related to climate change are also expected to increase in incidence (IPCC Working Group II, 1996; UNEP III, 1996). Health insurance will cost Canadians more in the future, either as tax payers or as individuals. If the health safety net in Canada becomes a two tier system then those who can afford their own medical care and have any of these ailments can expect to be paying very high health insurance premiums (Baker, pers. com,).

The whole economy can be expected to suffer as a consequence of the effects of climate change on the insurance industry. Insurance companies invest their funds in the financial sector. If funds in the insurance industry decline due to bankruptcy or having to pay out large amounts of money in claims, less will be invested in the local and global financial markets. If the insurance industry were to collapse due to more than one major catastrophe the financial markets will collapse too as trillions of dollars are removed from the system (Knox, 1996; Nutter, 1996; Flavin, 1994; Leggett, 1993).

The economy is affected at a more local level too. If the insurance industry decides to solve its risk problem and vulnerability to climate change by refusing coverage then disaster victims will have to be carried by the tax payer or individuals will have to pay the price themselves. In many cases this could mean the loss of everything. The unavailability of insurance coverage also makes it difficult for an economy to recover after a disaster as witnessed by the situation in Florida following Hurricane Hugo. Insurance coverage was withdrawn and lenders were unwilling to make the loans necessary for reconstruction without the availability of insurance. Even if insurance is available but the premiums have become exorbitant, then many new and existing business ventures will no longer be feasible because of high costs (IPCC Working Group II, 1996; Knox, 1996; Nutter, 1996; Deering, 1994; Flavin, 1994; Swiss Re, 1994).

Further socio-economic implications of climate change and its effects on the insurance industry are that the collapse of the insurance and financial sectors could lead to the loss of jobs (Nutter, 1996). Without adaptation on the part of all concerned it is possible that such a scenario could occur. Some hold even more drastic opinions of what will happen if we do not adapt and the possible effects of climate change are not built into the insurance industry's assessment of risk. Rudolf Kellenberger, a member of Swiss Re's executive board wrote in a Swiss Re report: "The more quickly and radically the global climate changes, the more extreme weather patterns could cause damage which not only pose a threat to individual citizens, families and enterprises but could jeopardise whole cities and branches of the economy - on a global scale - entire states and social systems." (Swiss Re, 1994). Economic devastation in general will lead to loss of livelihoods, poverty and in extreme cases homelessness.

ACTIONS BY THE INSURANCE INDUSTRY TO MITIGATE CLIMATE CHANGE

The insurance industry is not taking the possibility of climate change lightly. In November 1995 the United Nations Environment Programme Insurance Initiative was launched with a Statement of Environmental Commitment by the Insurance Industry. This has been followed up by a position statement submitted by the industry to the Climate Change negotiations in Geneva, 9 July 1996. In this statement the industry calls for early and substantial reductions in greenhouse gas emissions; further scientific research that establishes what level of greenhouse gases is likely to be dangerous; the establishment of a transparent framework of political, social, and economic measures that will promote sustainable development while taking into account the risks of climate change; and the position of the insurance and reinsurance sector to be represented when discussing or negotiating possible solutions to the problem of climate change (UNEP III, 1996).

On less of a policy level and more of a practical level, some insurance companies have invested and are investing in environmentally safe technologies[5] thereby creating a kind of climate venture fund. Another possibility is to disinvest in companies that contribute to greenhouse emissions. A precedent has been set for dumping stock in oil and coal companies for instance by health insurers who've sold their stock in tobacco companies. The industry is also lobbying for tighter building codes that improve energy efficiency and enable buildings to withstand the ravages of the weather (Deering, 1994; Flavin, 1994; Howard, 1995; Leggett, 1993).

RECOMMENDATIONS

As can be seen from the discussion above and the reference list, literature on the insurance industry and climate change on the prairies (especially the Canadian prairies) is limited if not non-existent. Also, the vast majority of the discussions focus only on property insurance. Since agriculture is one of the most important economic activities on the prairies, a greater understanding of the implications of climate change for the crop insurance industry is required. There is also very limited information about the interaction between health and climate change/variability. Impacts on health will inevitably be passed on to the insurance industry too. The greatest problem facing insurers right now - regardless of where in the world they operate - is that of assessing risk related to climate change.

Thus the author makes the following recommendations:

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[5] The Prudential has set a precedent in this regard. They invested US$200 million in Lutz of California, the largest solar-thermal operator in the world before it became bankrupt in 1991 (Legett, 1993).

1) Understanding of climate variables and how they interact to influence weather and climate on the prairies needs to be deepened. This understanding needs to be differentiated across the region in recognition that weather and climate varies across the region and that different parts of the region will be affected differently. The resolution of current GCMs is still too coarse to be able to provide insurance companies with the kind of information that they need for setting fair and realistic premiums in the face of climate change.
2) More study needs to be done on the kinds of risk that insurance companies can expect to incur when covering climate related damages on the prairies. Can insurance companies expect to cover more hailstorms? Will drought become a more frequent factor to contend with? Are crops more susceptible to pests as a result of warmer weather? Will health ailments increase with higher temperatures and more dust storms etc.?
3) Scientific, financial, and statistical analyses and the use of remote sensing and other techniques have already been used individually by insurance companies in assessing risk related to weather events. However, developing the links between these methods and using them in conjunction will enable insurance companies to more accurately assess their risk and project future losses.
4) The possible effects of climate change on the health of individuals in the prairies needs to be thought through. This information should be built into any decisions that are made with regard to reforming the health system.

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APPENDIX E

THE EFFECTS OF CLIMATE CHANGE ON RECREATION AND TOURISM ON THE PRAIRIES: A STATUS REPORT

THE EFFECTS OF CLIMATE CHANGE ON RECREATION AND TOURISM ON THE PRAIRIES: A STATUS REPORT

Marion Meyer
International Institute for Sustainable Development
Winnipeg, Manitoba

EXECUTIVE SUMMARY

Outdoor recreation is extremely dependent on the natural resource base and the weather. The resource base determines what kind of activities take place - for example, without water people cannot go swimming or sailing- while the weather determines when the activity will take place. Recreational choices are not only affected by the weather but also by socio-economic factors such as cultural norms, levels of disposable income, school/other holidays, the attractions present and the attractions offered elsewhere.

It is generally expected that temperatures will rise in the prairie provinces while there is less agreement on whether there will be more or less rain and snow. Higher temperatures, though, are expected to lead to lower water levels in the lakes and greater plant growth making swimming, fishing, sailing and water skiing less pleasurable. The season for these and other summer activities will be extended by the higher temperatures, though. The grassland ecozone is also expected to shift north. Wildlife can be expected to move with the ecozone. It is uncertain, however, how quickly this will happen. Rapid climate change could mean that many plant and animal species are unable to adapt and may become extinct in the process. Hunters and wildlife enthusiasts will more than likely follow the wildlife north or learn to hunt and view other forms of wildlife that move into the areas that they themselves usually frequent.

A longer summer does pose a threat to winter activities such as cross-country and downhill skiing, snow shoeing, skating, ice fishing etc. Less snow cover and a shorter winter season could threaten the livelihoods of ski resort operators who have the potential to go out of business. The indirect effects of this include the loss of tourism revenues to local restaurants, hotels and other forms of amusement as well as the loss of jobs for people within the community.

Since the loss of subsidies such as the crow rate, many rural communities have been considering recreation and tourism as a means of diversifying and strengthening their economies. Without knowledge of the interaction between this sector and climate change, communities could be making an economic choice which can potentially be undermined by the weather and climate change. For this reason the author has made the following recommendations:

- Climate change scenarios need to become more locale specific,
- A deeper understanding of the economic costs of creating favourable recreation conditions is needed,
- A comparative study needs to be conducted of competing attractions in places bordering on the region and the costs of engaging in these activities,
- New management strategies need to be developed to take into account the changing resource base in its effect on vegetation, wildlife and recreational choices, and
- Resource conflicts due to competition for scarce resources such as water need to be anticipated and legislation or a process established for resolving these conflicts.

INTRODUCTION

Tourism and recreation both affect and are affected by the natural and economic environment and changes to it. Many prairie communities, being faced with changes in their economy due to the loss of subsidies and the concomitant effect on agriculture, are looking to tourism as an alternative source of income and a way to bolster their economies. This is a response to a changing economic environment but what of a changing natural environment? What are the implications of climate variability and possibly change for this economic choice? While many factors such as culture, age, level of disposable income, available leisure time, and climatic conditions play a role in people's tourism and recreational choices, the focus of this paper is the effect that changing weather and climate have on the tourism and recreation sector.

The natural resource base is a necessary part of outdoor recreation, be it water for sailing, swimming, fishing etc.; or snow for skiing, snow shoeing or tobogganing; or wildlife for viewing or hunting. Climate change and variability are expected to affect ecological zones pushing the prairie region north. As ecozones and the resource base adjust, recreational activities will adjust with them. Weather patterns (temperature, rainfall, wind, snow conditions etc.), on the other hand, influence when recreational activities take place. Hence, this paper looks at how the resource base could change in the light of climate variability and change along with a change in weather conditions, and how they will affect the mix of activities that people engage in for recreation. The socio-economic consequences of a changing mix of recreational activities are also reviewed in order to gain a holistic picture of the kind of impacts that can be expected and that the tourists in the prairie region will have to adapt to. Following this, some recommendations will be made for further research relating to this topic.

This paper is based on a literature review of articles and papers relating to climate change and recreation on the Canadian prairies. Very limited literature was found on this topic specifically. Most of the literature found related to Saskatchewan, with one paper from Alberta. For this reason, the scope of this review is fairly limited. Its usefulness, however, lies in the knowledge gaps that are revealed. These gaps that are identified form the basis for recommendations for further study.

RECREATION AND TOURISM

Recreation and tourism can be defined in a variety of ways. The first is to make a distinction between recreation - for the purposes of this paper, the pursuit of outdoor activities by residents of the three prairie provinces or visitors - and tourism. Tourism refers to trips taken that exceed being away from home for longer than one night and that do not have work or commuting as their purpose. It often includes the pursuit of recreation. Tourism can also be categorised by who is doing the traveling. So it becomes possible to talk about domestic and international travel, which refers to people crossing the Canadian border (Wittrock et al., 1992).

Recreation can be broken down according to the season and the type of activity. Thus, Masterton et al. (in More, 1988) refer to winter season (the period between the first and last dates of snow cover of 2.5cm) and summer season (the period starting two weeks after the last date of snow cover) recreation. Outdoor recreational pursuits are then classified by the type of resource base that is required for the activity: dry-terrain (e.g., golfing, picnicking, walking, camping); water-based (e.g., sunbathing, swimming, bathing, fishing); and snow- and/or ice-based (e.g. nordic skiing, alpine skiing, snowshoeing, snowmobiling, tobogganing, ice fishing, skating). It is obvious from the above examples that outdoor recreation is extremely dependent on the resource base and on the weather. Weather will influence the way people use outdoor recreational facilities as well as their demand for outdoor experiences. It is important to realise, however, that what recreation and how much takes place is not only affected by the weather but also by socio-economic factors such as cultural norms, levels of disposable incomes, school/other holidays, the attractions present and attractions offered elsewhere. An example is the shift in people's preferences from consumptive recreation (e.g. hunting) to appreciative recreation (e.g. hiking) which increases the demand for pristine environments and parks (More, 1988; Arthur and Chorney, 1989; Wittrock et al., 1992).

Tables 1 to 3 show what recreational activities are engaged in on the prairies at present along with the climatic requirements for them.

Table 1: Climatic criteria for outdoor recreational activities[1] (Masterton in Wittrock et al., 1992)

Activity	Temp (^{0}C)	Visibility (km)	Thick Cloud Cover (tenths)	Hourly wind (km/hr)	Snow cover (mm)	Precipitation
Landscape touring	-24 to 32	>4.8	not applicable	<42.8	not applicable	nil
Skiing	-14.4	>0.8	not applicable	<25.7	25.4	nil to light
Snow-mobiling	>-21.1	>0.8	not applicable	<25.7	>25.4	nil to light
Passive Activities	>12.2	>1.6	<8	<33.8	not applicable	nil
Vigorous Activities	12.8 to 31.7	>3.2	<8	<33.8	not applicable	nil
Beaching Activities	>17.8	>1.6	<8	<25.7	not applicable	nil

Table 2: Minimum climate related requirements for summer recreation activities (More, 1988)

<table>
<tr><th colspan="6">Water Based Activities</th></tr>
<tr><th></th><th>Motor Boating</th><th>Water Skiing</th><th>Sailing</th><th>Fishing</th><th>Swimming/ Sunbathing</th></tr>
<tr><td>Air Temperature (^{0}C)</td><td>15 to 35</td><td>18 to 35</td><td>10 to 35</td><td>15 to 30</td><td>15 to 30</td></tr>
<tr><td>Wind (km/h)</td><td><50</td><td><15</td><td>15 to 50</td><td><15</td><td><15</td></tr>
<tr><td>Water Temperature (^{0}C)</td><td>2 to 20</td><td>10 to 20</td><td>10 to 18</td><td><18</td><td>15 to 20</td></tr>
<tr><td>Precipitation</td><td>nil</td><td>nil</td><td>nil</td><td>nil</td><td>nil</td></tr>
<tr><td>Lake size:
• Minimum (ha)
• Maximum (ha)</td><td>
>80
400</td><td>
>100
800</td><td>
>30 to >100
800</td><td>
20 to 80
400</td><td>
20 to 40
800</td></tr>
<tr><td>Lake depth (m)</td><td>1.5 to 2.5</td><td>>2.0</td><td>1.5 to 2.0</td><td>0.5 to 1.0</td><td>0.5 to 2.0</td></tr>
<tr><td>Carrying Capacity</td><td>1 ha/boat</td><td>5 ha/boat</td><td>10 ha/boat</td><td>--</td><td>--</td></tr>
<tr><td>Aquatic Vegetation</td><td>Minor emergent</td><td>minor submergent</td><td>Minor submergent</td><td>Minor emergent</td><td>Nil</td></tr>
<tr><th colspan="6">Dry Terrain Activities</th></tr>
<tr><th></th><th>Camping</th><th>Picnicking</th><th colspan="3">Golf</th></tr>
<tr><td>Air Temperature (^{0}C)</td><td>>10</td><td>10 to 25</td><td colspan="3">10 to 30</td></tr>
<tr><td>Wind (km/h)</td><td><10</td><td><20</td><td colspan="3"><20</td></tr>
<tr><td>Precipitation</td><td>Nil to light</td><td>Nil</td><td colspan="3">Nil</td></tr>
</table>

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[1] Where summer activities are divided into passive activities (e.g. gardening), vigorous activities (e.g. football), and beaching activities (e.g. suntanning).

Table 3: Climatic requirements for winter recreation activities (More 1988)

Environmental Condition	Nordic Skiing	Alpine Skiing	Snow Shoeing	Snowmobiling
Snow Season	**November to April**	**November to May**	**November to April**	**November to April**
Snow depth (cm)	20 to 30 minimum 60 optimum	20 to 30 minimum 60 optimum	20 to 30 minimum 60 optimum	30 minimum 60 optimum
Snow Density (g/cm^3)	<0.6	<0.6	0.2 to 0.6	0.4 to 0.1
Air Temperature (^0C)	-2 to -15	5 to -20	10 to -40	10 to -30
Snow making (^0C)	-6 to -15	-6 to -15	Not applicable	Not applicable
Wind (km/h)	<20	<15	<45	<45
Wind Chill ($watts/m^2$)	700	700	1600	1400

Requirements for recreational activities may change with technological advances in clothing and equipment and with the evolution of individual recreational activities (More, 1988). These advances are examples of adaptation to weather conditions and can be expected to take place in the face of climate variability and change too.

A study conducted in Saskatchewan of the province's tourism attractions revealed that the diversity of natural resources was one of the province's most important assets. Other tourism assets listed were uncrowded, unspoiled, clean surroundings; agriculture; the north; laid-back, friendly people; history and heritage. These assets can be extended to include all three provinces due to the similarities amongst Manitoba, Saskatchewan and Alberta (Wittrock et al., 1992).

Given that the diversity of natural resources is one of the prairies' greatest recreational assets, climate change and variability could have a significant impact on them as a tourist attraction. In order to gain insight into the effect of climate change on recreation on the prairies it will be useful to know how these assets will be affected by climate variability and then how the mix of recreational activities will change as a result of changes in the resource base which supports recreation and tourism (Wittrock et al., 1992).

IMPACT OF CLIMATE ON THE MIX OF RECREATION ACTIVITIES

Climate change scenarios for the prairies

Prairie climatic conditions have always been varied and to a degree unpredictable. The prairie climate is characterised by droughts and dry spells, early and late frosts, cold spells, excessive moisture and flooding. It is a climate of extremes with minimum temperatures dropping below -400C in January and rising to a maximum of between 350C and 400C in July. Annual precipitation is between 250 and 450mm, with more than two thirds occurring during summer (May to August) months. Passages of cold fronts, depressions, and numerous storms generate strong winds throughout the year. Dust storms are frequent during drought years but have also been found to occur during relatively short lived dry conditions (Jones, 1996; Cohen et al., 1992).

Various General Circulation Models have been used to project climate change scenarios if a doubling of the concentration of carbon dioxide in the atmosphere were to occur. Most models predict that temperatures will increase for both summer and winter, and that the variability observed in the current climate will continue under climate change. There is less agreement about whether precipitation (in the form of both rain and snow) will increase or decrease but there is agreement that the availability of water will diminish due to high temperatures and evapotranspiration (More, 1988; Cohen et al., 1992; Wittrock et al., 1992; Wittrock, 1993; Jones, 1996).

These conditions are expected to have significant effects on the water resources available to inhabitants of the prairies, the vegetation and wildlife populations. What follows is a brief assessment of how these resources are expected to be affected increased climatic variability and change. A lot of this is speculation since GCMs embody inherent uncertainties due to the complexity of the system being modeled and also because the models are still not fine enough to cover changes on a micro scale in any kind of detail (Cohen et al., 1992).

Water resources

Many of the surface waterbodies (lakes, rivers and reservoirs) in the prairies tend to be shallow and eutrophic. Water quality and quantity affect recreation directly (see Table 2). Climate variability is expected to alter lake levels and affect the salinity and flora and fauna composition of the lakes. Warmer temperatures and shallow depth will result in warmer water which encourages algae and plant growth. Increased algae and plant growth take up large amounts of oxygen and, in the case of shallow bodies, may lead to the expiration of fish life due to a reduction in dissolved oxygen. Warmer temperatures could also mean a later freeze and an earlier melt of ice on lakes, rivers and reservoirs. Decreased run-off and shorter run-off periods are also predicted by some climate change models (More, 1988; Wittrock and Wheaton, 1992; Wittrock et al., 1992).

Vegetation

The distribution of vegetation is closely related to climate. Thus, all vegetation types, be they grasses, wild flowers, fungi or large coniferous trees, will be affected by climate change. The prairies are characterised by grassland vegetation which is drought resistant and tolerant of temperature and precipitation extremes. The prairie ecozone spanning the three provinces is bordered by the boreal forest which is less suited to temperature extremes and drought. Various climate change scenarios suggest that the climate of the boreal forest will be replaced by that of the prairie ecozone because of warmer and drier conditions. Thus, it can be expected that the prairie ecozone with its grassland species will expand northward. Which species will migrate and which species will become extinct, however, are difficult to predict since species adaptation and migration depend on a number of factors. Soil types, how they reproduce, daylength preferences and the types of predators and competition all have a bearing on this. Also, adaptation tends to occur slowly rather than quickly. Current climate change scenarios based on a doubling of the concentration of carbon dioxide in the atmosphere do not predict how quickly a doubling will take place. They are also too sparse in their application to specify regional and local changes in the kind of detail that is necessary for predicting species adaptation, migration, and extinction (Wall, 1989; Lopoukhine, 1991; Wittrock et al., 1992).

Wildlife

Wildlife is directly dependent on vegetation for food and shelter. Changes in habitats and the decreased severity of winter will result in alterations of the distribution and numbers of major big game, waterfowl, and upland game bird species. As the prairie ecozone displaces the boreal forest, species that are adapted to the prairies and aspen parkland can be expected to increase in these areas. Milder winters may also mean higher winter survival rates of species not adapted to cold and snow. The drying up of potholes that is expected to accompany rising temperatures will in all likelihood also lead to the reduced production of waterfowl. Lower lake levels could also lead to the exposure of nesting sites to predators (More, 1988; Wittrock et al., 1992).

Effect on recreation activities

Recreationists have a degree of flexibility in their response to these impacts. Travelling to alternative locations with favourable conditions, reducing participation when conditions are unfavourable or ceasing to participate in their usual activities at all, are all options that can be pursued. People can also undertake new activities or increase their involvement in other activities. The constraining factors will be free time and personal economic well-being (More, 1988). Putting these constraints aside, the effect of changing weather patterns and climate is looked at below.

Warmer temperatures will have a great effect on recreation and tourism. The magnitude of this effect is still to be determined, however. Warmer water and air temperatures are expected to increase swimming activity which will also stretch over a longer period of time. However, a decrease in the quantity of water and quality of the resource will reduce swimming activity. Table 2 shows that no aquatic vegetation is conducive to swimming. The expected increase in algae and plant life will inhibit swimming. It will also have a negative effect on fishing. If fish populations decrease because of a lack of dissolved oxygen, fishing may be ruled out as a recreational activity at many spots where it now takes place. Increases in air temperature will likely result in a longer season in which water based and dry terrain activities can take place. Decreased lake area and depth due to rising temperatures could result in less opportunity for sailing, boating and water skiing, however. This is especially true if boat docks become stranded above the water line and new docks have to be built. Decreased run-off and shorter run-off periods in the spring and early summer will also influence the quality of white water rafting and kayaking. While the summer season may be extended and provide more opportunities for outdoor recreational activity, it is uncertain whether this extended season will be taken advantage of. People's recreational choices are not only influenced by the weather but also by the amount of leisure time that they have available to them. So, the bulk of recreational activity may continue to take place at the same peak times as it does now: around the school holidays (More, 1988; Arthur and Chorney, 1989; Wittrock et al., 1992).

An extended summer season does not bode well for activities such as skating, ice fishing, and lake snowmobiling, though. The season for these activities is expected to be shortened substantially since at least 15cm of ice is necessary to support the weight of an adult. (More, 1988; Wittrock et al., 1992). Other winter activities such as cross-country and downhill skiing are also expected to be affected. A study in Quebec (Lamothe et al., 1988) revealed that the downhill ski season can be expected to be shortened by 50 to 70 percent as a result of climate change. More (1988) and Wittrock et al., (1992) express the same concern for the prairie provinces, although they have not quantified by how much the season can be expected to be shortened. If snow storms come later in the Fall, there may be insufficient snow for both types of skiing during the Christmas holiday season (peak ski season). There may also be insufficient water, money and time (before this period) to make snow which will meet the requirements (see Table 1) for the sport. Making snow for cross-country skiing is also impractical because of the large area that has to be covered. Higher temperatures could draw more people to skiing venues when the conditions are suitable (More, 1988; Wittrock et al., 1992).

Golfing, picnicking and camping opportunities will all increase because of the warmer and longer summers. Irrigation and the costs thereof can be expected to increase for golf courses, camping and picnic grounds maintenance as a result of low rainfall and high evapotranspiration rates.

Scenarios of vegetation change and resulting movement of wildlife indicate a higher survival rate for species that enjoy warmer winters. Many of the prairie species will move north. Wildlife enthusiasts and bird watchers can look forward to more sitings of winter survivors and they may travel north in order to view wildlife which they usually view in the south now. Hunting activities can be expected to shift north along with the wildlife population. This may have implications for out of province hunters who will have to travel longer distances in order to hunt. They may be unwilling to do so, especially if the costs become prohibitive. The species hunted are also likely to change as hunters adjust to new species in their habitual hunting grounds. As the demographics of the region alter hunting patterns will more than likely alter too. More rural people than urban people tend to hunt. If agriculture in the south becomes less viable because of climate change, there will be fewer farmers and hence fewer hunters (More, 1988; Wittrock, 1992).

SOCIO-ECONOMIC AND ENVIRONMENTAL CONSEQUENCES OF A CHANGE IN THE MIX OF ACTIVITIES

Tourism and outdoor recreation benefit the economies of many communities. Now, with the loss of subsidies such as the crow rate, more and more communities are looking toward the recreation and tourism industry as a way of diversifying their economies. As the climate and the mix of recreational activities changes these economies can be expected to be affected. If communities do not have access to information on the relationship between recreation and the possible effects of climate change, they could be making decisions to diversify their economies in an unsustainable way.

Unfortunately, very little analysis has been done on how, and the degree to which, economies will be affected by the impacts of climate change on recreation and tourism. Speculation is that for those activities that cost recreation managers little in capital development or operating expenses, the economic impact of shifting recreation patterns will be negligible. Activities involving facilities that are costly to construct and maintain are expected to incur the greatest economic repercussions. Downhill and cross-country skiing are examples of such activities. A study in Alberta (More, 1988) found that consumers will invest large amounts of time and money in these activities. However, they expect to have a satisfying experience. If conditions are sub-optimal and the activity becomes costly then they are likely to alter their recreation habits. Making snow is costly and resorts will have to recoup this cost through revenues. If attendance drops it is likely that many ski resort operators could go out of business. The indirect effects of this include loss of tourism revenues to local restaurants, hotels and other forms of amusement as well as the loss of jobs for people within the community (More, 1988).

Tourism and recreation activities do not take place in a vacuum and as such interact with many other sectors. The most obvious on the prairies being agriculture. As has already been mentioned, many of the outdoor recreation activities on the prairies are dependent on the availability of water in large quantities. As the prairie region gets drier and experiences more drought conditions recreational water users will be competing with farmers and industry for that water source. This holds the potential for conflicts among users for limited supplies of good quality water. Other resource conflicts that can arise are between recreationists and the forestry, mining and commercial fishing industries (Wittrock and Wheaton, 1992; Wittrock et al., 1992).

Environmentally speaking, the migration of recreational activities northward along with the ecozone could lead to pressure on vulnerable wilderness areas. Longer, warmer summers may lead to greater visitation to parks which could result in degradation, over development and over use. Fewer hunters in the south could also mean overpopulation of big game species which would require new management techniques (More, 1988; Witttrock et al., 1992).

RECOMMENDATIONS TO ENHANCE ADAPTATION

In order for the tourism and recreation sector to adapt to climate change, more information is necessary on all aspects. Very little research has been done to date on what this sector can expect on the prairies. Current general circulation models are not fine enough to reflect possible changes at specific locations in the prairies. Scenarios still refer to general locations within the region. As scenarios become more specific to locales within the region changes in recreational activities can be anticipated and the necessary contingency plans made.

A deeper understanding of the economic costs is also required. So far very little has been done to determine what the costs will be of creating favourable conditions for swimming, golfing, winter skiing, etc. Since there is limited understanding of how consumers will respond to changing weather, conditions, and costs, it is difficult to know whether these costs can be justified. Hence, a study needs to be conducted on how consumers will adjust their recreational choices as well.

No mention has been made of competing attractions outside the prairie provinces and how people will respond to these if the conditions necessary for recreation on the prairies change. This is because the author was unable to find written material relating to this topic. To gain a realistic view of what can be expected to happen in the tourism and recreation sector as a whole it will be necessary to look at competing attractions elsewhere and their capacity to draw recreationists from the prairie provinces and elsewhere.

It is thought that the ecozone will shift northward as a result of climate change. More research is needed on this so that shifts in demographics, vegetation and wildlife populations can be better anticipated. As various users - both people and wildlife - begin to compete for increasingly scarce resources (especially water) new management strategies will need to be developed that take this into account. Resource conflicts need to be anticipated and legislation or a process established for resolving these conflicts.

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APPENDIX F

CLIMATE CHANGE AND ITS IMPACT

ON

WATER SUPPLY AND DEMAND IN THE PRAIRIE PROVINCES

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WATER SUPPLY AND DEMAND IN THE PRAIRIE PROVINCES

Adaptation and Impacts Section
Environment Canada
Regina, Saskatchewan

INTRODUCTION

In the Prairie provinces the interaction of a variable climate with a variable physiography produces a complex runoff pattern. The Prairie provinces are made up of seven ecozones: Prairie, Boreal Plain, Boreal Shield, Taiga Plain, Taiga Shield, Hudson Plain and Mountain Cordillera. The average annual runoff can vary from less than 1 cm on the plains to 5 cm on the Shield to over 27 cm in the mountains. The smaller the average annual runoff, the greater is its variability and sensitivity to climate variations. An annual runoff of zero is not uncommon in many drainage basins within the Prairie ecozone.

Water supply and demand will be most affected by climate change in the Prairie ecozone. Most of the population from the three provinces lives in this zone which includes the major centres of Calgary, Edmonton, Saskatoon, Regina and Winnipeg. Coupled with the water demand to support the population there are significant requirements for irrigation, power generation (hydro and thermal) and recreation. In many basins, the water resources are fully or nearly fully allocated. With annual evaporation exceeding precipitation on the prairies, water supply is dependent on snowmelt runoff from the prairie and mountain regions to replenish lakes, reservoirs, wetlands and groundwater. Any alteration to the critical balance of this cycle could have a significant impact. Climate change may, for example, affect the timing of runoff and precipitation, the form or amount of precipitation, or the amount of evapotranspiration.

CLIMATE CHANGE AND HYDROLOGY

To assess the impacts of climate change on water supply and demand it is first necessary to understand how the climate may be modified over the region. Several studies have attempted to assess the possible impact of climate change on Canada. and most base their analysis on a climate projection generated by a computer-based general circulation model (GCM) of the climate system (Environment Canada, 1994).

Cohen et al. (1989)[1] and Cohen (1991)[1] estimated climatic change impacts on the Saskatchewan River Basin, which encompasses most of the Prairie Ecozone, using scenarios based on the following General Circulation Models (GCMs):

- GISS (Goddard Institute for Space Studies, 1984 and 1987 interpolations)- Streams that originate in the prairie region would have a marginally higher runoff, but the streams that originate in the mountains would have an increase in flow when compared to the 1951 to 1980 normals

- GFDL (Geophysical Fluid Dynamics Laboratory, 1980 and 1987 versions)- GFDL87 - decreased runoff for both the mountain and prairie originating streams.- GFDL80 scenario - increased flow for northern regions, while the southern grid points had well below normal flows. In fact, some locations along the Alberta-Saskatchewan border show zero runoff

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[1] As cited in Wheaton et al., 1992

- OSU (Oregon State University)- Runoff differed little from those with the normal 1951 to 1980 climate.

The CCC90 GCMII (Canadian Climate Centre 1990 General Circulation Model) scenario projects lower than normal snowfall amounts for Saskatchewan . A reduction in snowfall would have a great impact on the amount of spring runoff from meltwater. However, the amount of total precipitation is expected generally to increase in winter months in Saskatchewan, thus further influencing the snowcover. The increase in precipitation during winter is projected to be in the form of rain. When rain falls on a snowcover, the snowcover changes considerably. Changes include reduction of snowcover and increases in ice layers and density. Such changes in the snowcover will have implications for other sectors as well as for the water resource sector. These other sectors include the recreational and tourism industry (such as cross country skiing and snowmobiling, which need a continuous snow pack), wildlife, agriculture and wetlands. The intensity and timing of the runoff from snowmelt would also be affected (Wheaton et al., 1992).

From Wheaton et al. (1992), the following, sometimes conflicting, interpretations of model results give an indication of the possible impacts on the hydology

- Cohen et al. (1989) draw some conclusions about the effects the changes implied by these scenarios will have on the agricultural sector. A GISS84-type climate with an increase in the water demand in the agriculture sector would not have much effect on the other water users. The situation would be similar with the OSU scenario. In contrast, the GFDL scenarios would have serious implications for the whole range of water users. There would have to be a major policy response to the water shortage.

- The decrease of runoff shown by the GFDL scenario results (e.g. Cohen et al., 1989; Cohen, 1991; Thomas, 1990) would have serious implications for the amount of water available. On the other hand, the increase in runoff shown by the GISS results would allow for potential increases in water supply (Bjonback, 1990).

- Thomas (1990) remarked that although GCM results project a decrease in the magnitude of the snowpack and an early disappearance of the snowpack, clear agreement is lacking about the hydrological consequences of these effects. Thomas suggests that the use of surface models that vary in complexity makes it difficult to make direct comparisons of the results.

- Some of the GCM scenarios for an equivalent doubling of CO_2, indicate an increase in the amount of average annual precipitation, a larger number of extremes in weather and greater frequency of severe storms, e.g. thunder storms. Such consequences could, in turn, cause problems in storm drainage systems, and runoff extremes could affect flood control measures and speed up the deterioration of dams and flood control structures (Schwarz and Dillard, 1989).

- The climate change scenarios show increased annual precipitation. What they do not show is the change in intensity and the timing of the extreme precipitation events. According to Jacobs and Riebsame (1989), and Riebsame (1989), more intense precipitation events over durations measured in hours or days would cause more variability at time-scales that are of interest to flood managers. Extreme precipitation events for periods of months or years would give rise to variability that would be of greatest interest to water supply planners. More research is needed regarding possible changes in intensity of rainfall events and changes in precipitation variability.

- The climate has been characterized by extreme weather events in the past, such as floods and droughts which can have serious implications for sectors such as agriculture, energy and human health. This has led to the construction of many structures (e.g. dams, weirs etc.) to minimize the impacts of these extreme events. Yet these structures were designed on the basis of the magnitudes and flood frequencies of past events, not for what may happen with future global warming. The magnitude and frequency of extreme events could increase with global warming (Jacobs and Riebsame, 1989; Lins et al., 1990). The timing and amount of spring runoff will also change with global warming (Nemec, 1989).

- Nicholaichuk (1991) states that there will be changes in stream flows and flood risks. He also cites results of Haas and Marta (1988), who used the GISS84 and GFDL87 GCM results for $2xCO_2$, to estimate runoff. Their results, which indicate an increase in the number of flood events, found the probability of droughts would not be affected. Unfortunately, the term drought was not defined in Nicholaichuk's article and there are several different definitions for the term drought. The definitions depend on what type of drought is being considered (e.g. hydrologic drought vs agricultural drought).

- Jacobs and Riebsame (1989) acknowledge, however, that the analysis of changes in climate variability and extreme events is just beginning. There is no conclusive evidence that there will or will not be an increase in the number and intensity of extreme events. Floods are difficult to predict because they are short term events, measurably influenced by instantaneous peak flows. The timing and severity of floods are not closely related to monthly or annual runoff.

Depending on the model selected, the predicted prairie runoff could vary from below normal to above normal. While GCMs agree on large-scale changes to the climate system, GCMs have so far provided little insight into the variability of future climates and regional projections must be treated with caution (Environment Canada, 1994) There are indications that in general, for example,

- summer hot spells in the Prairies could become more frequent, while extreme cold spells in winter would become less frequent
- precipitation patterns will change
- evaporation will increase

There is also uncertainty regarding timing and intensity of extreme events, such as floods and droughts (Wheaton et al., 1992) In addition, temperature increases may not be linear - major or sudden surprises are distinct possibilities (Environment Canada, 1994) All attempts to construct scenarios of the possible impact of climate change are affected by these and other uncertainties. The model scenarios must therefore be recognized as the best assessment possible on the basis of existing scientific knowledge. (Environment Canada, 1994). This highlights the need for further research to improve the understanding of climatic hydrological processes (Wheaton et al., 1992).

WATER SUPPLY

The inability of the current suite of GCMs to reliably predict climate parameters on a regional scale makes it very difficult to predict the impact on the water supply with any confidence. Cohen et al. (1992)[1] state that it may be appropriate to consider two main types of future situations for the Canadian prairies:

1. "Dust Bowl" scenarios in which reduced snow cover in the Rocky Mountains reduces water supply in the main stream channels and soil moisture is reduced in the semiarid zone. This scenario would result in more frequent and intense hydrological, agricultural and other types of droughts; and
2. "Opposing Stresses" scenario in which increased snow cover in the Rocky Mountains is combined with reduced soil moisture in the prairie region. This would mean that the prairie region would have to meet new demands for increased protection from spring floods, while providing increased water supply services to downstream areas due to increases in drought frequency and intensity.

The literature exploring the effects of climatic change on water quantity is extremely limited for the Canadian Prairies (Wheaton et al., 1992). Schwarz and Dillard (1989)[1] examined the Saskatchewan River basin which covers much of the prairie ecozone and includes major population centres in Alberta and Saskatchewan. Its water resources are dependent on the snowfall and snowmelt regime in the mountains. There is no consensus on projected changes in runoff from the Rocky Mountains (Environment Canada, 1994) but if the annual snowpack in the mountains is reduced, there will be a significant impact on the supply of water that flows through the basin The timing of this snowmelt is also critical. If the melt is early and rapid, producing a runoff that exceeds the storage capacity of the reservoirs on the rivers, water will have to be released. This could lead to a shortage of water later in the year (Schwarz and Dillard 1989)[1].

There are a number of closed basins in the prairies that are replenished by surface runoff but have no outflow. These basins are particularly vulnerable to climate variability and change; for example, during the late 1980s, the water level of Old Wives Lake in Saskatchewan continually declined so that by 1988 it was completely dry. The lake then recovered following a series of wetter years. Farm dugouts are important rural water supply sources for domestic and agricultural use and are also sensitive to climate variations because they are usually designed on a two year return period. With climate change, the rural population will be particularly affected by changes in water supply (Wheaton et al., 1992).

Wheaton et al. (1992) provided a list of possible impacts of climate change for Saskatchewan and its water resources.

	Possible impacts of climate change	**Confidence**
Saskatchewan River(north & south)	System Reduction in mean annual flow by nearly 20%	Low (GISS84)
Spring Runoff	Increase in volume and spring runoff due to increase in fall and spring precipitation	Low -Medium
Summer Flows	Reduction in summer flow and increased duration of low flow	Medium
Evaporation	Warm temperatures may cause increase in rate of evaporation. However the effect of this may be offset by an increase in precipitation.	Low
Flooding	Increased fall precipitation combined with warmer, wetter springs may result in increase in frequency and magnitude of flooding.	Medium
Drought	Increase in summer temperature and earlier spring runoff may result in increased duration of low summer flows and occurrence of drought conditions.	Medium
Recreational Uses	Impact not known (effect of increased evaporation may be offset by increase in spring runoff).	Low
Ground Water	Impact not known	Low
Water Levels	May increase annual variation in water levels	Low
Hydropower Production	Impact largely dependent on effect of climate change on mountain runoff.	Low
Cooling Reservoirs for Thermal Power Plants	Possible increase in evaporation may be offset by increase in spring runoff.	Low
Erosion	Possible increase in frequency and magnitude of spring floods may increase rate of erosion and deposition.	Medium

Our society depends on a reliable supply of good quality water for survival. The difference between the supply of water and its demand is large on the Canadian prairies, even under present day conditions (Kienholz et al., 1989)[1]. In past drought years, such as 1988, many water quality and quantity problems were experienced (Wheaton and Arthur, 1989)[1]. Climatic change will result in changes in the patterns of precipitation and in effective loss of precipitation through temperature driven evaporation (Kellogg, 1989)[1]. This may cause water supply and quality problems to become even more critical than they are now in semi-arid to sub-humid climate areas. The lack of available water in 1988, for example, led to an increase in government assistance programs, and the dryness resulted in an increase in the consumptive use of water (Arthur and Chorney, 1989)[1].

WATER DEMAND

Water is needed to sustain life. It is required by several sectors of society, such as domestic, agriculture, industry, energy and recreation as well as by wildlife in general. Under a warmed climate with possibilities of less available water, each sector of society will be demanding action by the planners to ensure an ample supply of good quality water (Wheaton et al., 1994). As well, there will be increased demand for water in summer for such things as watering lawns and providing for the longer length of outdoor swimming season, for dust control (street cleaning), and for other aesthetic and public uses. More water will also be required to fight forest and brush fires (Pentland 1984)[1] .

Because of the warmer weather there will be a greater need for good quality drinking water for livestock, wildlife and humans. Water quality will deteriorate as the quantity of water decreases because the concentration of pollutants, sediment load and salinity will increase. Climate change impacts on wind and water erosion and chemical applications in agriculture will also influence the quality of water. There is a need for research to assess how global warming will affect water quality. The quality and quantity of urban and rural water supplies may have some impacts on people's health. Rural populations may have more problems because of the greater use of untreated water from wells and dugouts (Wheaton et al., 1994).

If climatic warming reduces the supply of good quality water, more intense conflicts may occur among users for the limited resource. They may arise between urban and rural or industrial and agricultural users, for example. Legislation will be needed to deal with such anticipated problems in advance (Diaz et al., 1984)[1] As well, the demand for interbasin transfers will change with global warming.

The largest single loss of water in the Canadian prairies is a result of evaporation (e.g. Nicholaichuk, 1991)[1]. High evaporation rates from reservoirs and lakes will reduce the availability of water for other uses. Evaporation rates in the future can be expected to increase further due to the increased temperatures.

The major consumptive use of the remaining water is by the agricultural sector through irrigation. When land is irrigated, as much as 70 percent of water in a channel is lost during the transportation of the water (e.g. in open canals). The irrigation water is consumed during the evapotranspiration process which occurs in living plants, and percolation down to the ground water. The unused water drains off as return flow to the river system. Irrigation could become an important issue among the various water users if there is only a limited amount of water available.

A major source of irrigation water for agriculture is the Saskatchewan River basin. It has been projected that the irrigation network within the Saskatchewan basin will expand. It is believed that by the year 2000 more than 500 000 hectares of irrigated land will be supplied by water from the Saskatchewan River basin (Cohen et al., 1992)[1]. Increases in irrigation would be dependent on constraints which include the availability of water, benefits of added production and impact on the environment. The various GCMs also indicate that runoff will likely occur at different times under increased greenhouse warming than at present (Wheaton et al., 1992).

For transboundary (international, interprovincial and provincial-territorial) river systems there are formal agreements with respect to how much water must move on to the next jurisdiction. These agreements were put to the test during the drought years of the 1980s. With future climatic change and with perhaps even less water to go around, these agreements will be further tested. Bjonback (1990)[1] predicts that if the level of water use continues at its present rate, there will be problems in maintaining the required flow for supporting fisheries and ecological uses.

A Master Agreement on Apportionment was signed in 1969 between Canada and the Prairie Provinces that defines the water allotment for each province. A major provision of the agreement commits Alberta to pass one half of the natural flow arising in or flowing through Alberta to Saskatchewan. Saskatchewan has a similar commitment to Manitoba. There will be increased demand for water with increasing temperatures and an upstream province may use more than its authorized share. This is possible because any of the parties could unilaterally pass legislation that would exempt it (Pearse et al., 1985:168)[1].

Agreements pertaining to international basins also exist. These include the Souris River (Saskatchewan and Manitoba), St. Mary River

(Alberta), Milk River (Alberta and Saskatchewan), and Lake of the Woods (Manitoba). Changes in flow, especially decreases associated with increased consumptive uses and evaporative demand, may also result in difficulty adhering to the agreements.

With climate warming all demands on the limited water resource on the prairies will increase. There may also be changes in the type of demand. For example, a warmer climate may make it feasible to change from dryland farming of cereal grains to higher value irrigated crops. Until the climate models are better able to predict changes on a regional basis we must surmise the impact on the demand.

WETLANDS

Wetlands are defined as "land that has the water table at, near, or above the land surface, or which is saturated for a long enough period to promote wetland or aquatic processes" (Tarnocai, 1980)[1]. Wetlands are maintained by a high water table or frequent flooding. A large supply of water in excess of losses is required. Climate controls the supply of water to the wetlands through precipitation and runoff, and controls the loss of water from wetlands through evapotranspiration. Climate also affects the hydrological status of the wetlands by influencing factors including vegetation development, frost formation and water infiltration into soils. Climatic variations have both direct and indirect effects on the supply and the losses of water and therefore affect the behaviour of the wetlands as well as the feasibility of preserving them (Woo, 1991)[1]. A strong relationship exists among climate, wetland hydrology, vegetation patterns, and waterfowl habitat. Climate affects the quality of habitat for breeding waterfowl by controlling regional water conditions, including water depth, areal extent, and length of wet/dry cycles (Cowardin et al., 1988)[1]. Climate also affects vegetation patterns, such as the cover ratio (ratio of emergent plant cover to open water) (Poiani and Johnson, 1991)[1].

Wetlands have many important roles in the environment and society, besides being significant in their own right. These roles include habitat for waterfowl, water plants and animals, surface water supply storage, connections to ground water, environmental aesthetics, recreation and microclimatic control. Wetlands are among the world's most productive environments. They provide significant benefits through the maintenance of the water table, water storage and flood control, shoreline stabilization, timber production, waste disposal and water purification, and recreation (Usher and Scarth, 1990)[1].

Although much of the extensive northern wetlands remain undisturbed by humans so far, warming may lead to increased human activity that will add to the natural stress that is likely to affect northern wetlands with climatic warming (Wheaton et al., 1992). In other parts of the prairies, wetlands have undergone considerable alteration in the last several decades, suffering from both human-induced and natural changes. This is especially true of prairie wetlands which have undergone human disturbance (e.g. drainage for agriculture and other uses) and drought-induced drying and disappearance. Over 71 percent of prairie wetlands in Canada have been lost due to human activities (Lands Directorate, 1986)[1]. Surveys conducted by the Canadian Wildlife Service, Environment Canada (Brace and Pepper, 1984)[1] indicate that wetland destruction is greatest in Saskatchewan, at 21 percent, as compared to the other prairie provinces. Agricultural degradation of wetland margins also is occurring. On the average, 78 percent of wetland margin area in Saskatchewan has been degraded, 64 percent in Manitoba and 93 percent in Alberta (Brace and Pepper 1984)[1]. Saskatchewan Environment and Resource Management (1997) indicates that while agricultural impacts on wetland basins in Saskatchewan have remained steady since 1981, there has been a steady increase on the wetland margins affected, rising from about 60 percent to about 86 percent.

Wetland destruction (amount and rate) may also be affected indirectly by climatic variations (including short term variability and longer term change). In warmer and drier years, wetland margins and entire wetlands are easier to cultivate and are therefore more suitable for agricultural use. Thus, wetland degradation by agriculture and other activities may be accelerated with increased incidence of warmer and drier years (Wheaton et al., 1992). Wittrock and Wheaton (1989)[1] examined how the 1988 drought and earlier dry years affected waterfowl populations. With the wetlands disappearing because of the dry weather and destruction of their habitat through cultivation, the migratory waterfowl are also being severely affected. Their populations have decreased during the dry 1980s and an apparent increase in diseases occurred, mainly due to overcrowding on the remaining wetlands. This indicates what may happen under a future warmed climate.

The prairie sloughs will suffer most drastically with global warming. These wetlands are also seriously affected by the variability of the present climate (Woo, 1991)[1]. The prairie sloughs have already suffered drastically in the extremely dry conditions of the 1980s. With continued warming and drying they may shrink in size and seasonal duration and then dry up altogether.

Few studies have examined the effect of climatic variability, especially global warming, on wetlands. Climate change could alter many of the hydrological and other wetland characteristics. The prairie wetlands appear sensitive to changes in snow melt and evapotranspiration, and these should be addressed in impact assessment. Less snow melt and more evapotranspiration would tend to decrease water level amounts in prairie sloughs. Scenarios for $2xCO_2$ indicate shorter snow seasons but greater precipitation amounts. The likely resulting effects on snow cover and snow melt amounts and wetlands are unknown (Wheaton et al., 1992).

RESEARCH GAPS

Climate models capable of predicting changes at the regional level, both spatially and temporally, must be developed to assess the impacts of climate change on water supply and demand.

A comprehensive assessment of the likely effects of global warming on water supplies and demands should be undertaken. Appropriate mitigative strategies should be formulated and implemented.

Changes to wetlands should be tracked with a coordinated ongoing monitoring program. More research should be done on wetlands ecology in its broadest sense. This would include the role of climate and climate change, and interactions with wildlife and fish. Important environmental indicators that can be used to help track changes in wetlands should be identified. Wetland ecosystems need to be evaluated, in both economic and non-economic terms. Land use and other programs and policies that affect wetlands should be updated to incorporate wetland conservation and restoration as objectives so as to try to assure sustainability in a changing climate. Every effort should be made to heighten public awareness of the general values of wetlands and thus to improve public support for sustaining wetlands in a changing climate (Wheaton et al., 1992).

There will have to be further research in socioeconomic adjustments and impacts in areas such as municipal water use, tourism and recreation, agriculture and power generation under a warmed climate (Cohen and Allsopp, 1988; Thomas, 1990)[1].

In past severe drought years, many water quality and quantity problems were experienced (Wheaton and Arthur, 1989)[1]. Climatic change will result in changes in the patterns of precipitation and in effective loss of precipitation through temperature driven evaporation (Kellogg, 1989). This may cause water supply and quality problems to become even more critical than they are now in semi-arid to sub-humid climate areas. The lack of available water in 1988, for example, led to an increase in government assistance programs, and the dryness resulted in an increase in the consumptive use of water (Arthur and Chorney, 1989)[1].

A large part of the prairies is dependent on snowmelt runoff from the Rocky Mountains. Research is required to assess the impact of climate change on the magnitude and timing of mountain runoff.

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APPENDIX G

LITERATURE REVIEW

CLIMATE CHANGE IMPACTS IN AQUATIC ECOSYSTEMS

IN THE

PRAIRIE PROVINCES

LITERATURE REVIEW
CLIMATE CHANGE IMPACTS IN AQUATIC ECOSYSTEMS IN THE PRAIRIE PROVINCES

Kevin J. Cash
Canadian Wildlife Service, Environment Canada
Saskatoon, Saskatchewan

INTRODUCTION

The Canada Country Study (CCS) has been initiated under Environment Canada’s ‘Clean Air Campaign’. The purpose of the CCS is to provide a coherent national assessment of climate impacts and adaptation for Canada. Under Phase 1 of this program a series of short reports on sensitive sectors or issues within the Prairie Provinces are being prepared, these reports will then be condensed into a single report for the Prairie Provinces which in turn will contribute to a final national report. The purpose of this sectoral report is to provide a brief overview of measured and predicted impacts of climate change on aquatic quality within the Prairie Provinces; it will not concern itself with issues of water supply or demand as those are being addressed by another sectoral report.

Accompanying this report is a bibliography of literature relevant to climate impacts on aquatic quality within the Prairie region. The bibliography contains studies unique to this region as well as studies conducted in other areas but deemed relevant to aquatic issues within the Prairie Provinces. This report does not attempt to summarize or review all literature in the bibliography. Rather, a smaller subset of papers will be cited where appropriate in order to illustrate specific issues.

Although the focus of the CCS is on the assessment of impacts resulting from climate change, climate change itself is but one component of the larger and more complicated issue of environmental change. Environmental change is partly a consequences of increasing atmospheric concentrations of greenhouse gases (primarily CO_2) but is also a consequence of other types of change such as land use/cover changes and alterations in the global nitrogen cycle. Not only does environmental change extend beyond climate change but the components of environmental change are themselves highly interrelated. For example, while they occur locally as discrete changes, collectively changes in land use/cover probably constitute the single largest component of global environmental change. Changes in land use/cover impact both climate and the nitrogen cycle while changes in climate and nitrogen use in turn influence land use (Vitousek 1992, 1994).

In keeping with the stated purpose of the CCS this overview will focus only on the impacts of climate change on aquatic systems within the Prairie Provinces but it must be noted that climate change occurs within a larger context. It will not be possible to successfully and coherently assess the ultimate impacts of climate change in isolation from the context in which they occur.

IMPACTS OF CLIMATE CHANGE ON AQUATIC SYSTEMS IN THE PRAIRIES

Although issues surrounding climate change, and global warming in particular, are increasingly the subject of study, the impacts of such change on freshwater systems have received considerably less attention (Carpenter *et al*. 1992; Vitousek 1994). This lack of study is particularly apparent within the Prairie Provinces and the resulting information gap is especially significant in light of the fact that freshwater systems are critical to ecosystem sustainability and are tightly coupled to both climate and land use activities (Firth and

Fisher 1991; Carpenter *et al*. 1992). A major exception to this trend is the work that has been carried out in the Experimental Lakes Area (ELA) of northwestern Ontario. While not part of the Prairie region this work will be discussed both because of the physical proximity (and hence relevance) of ELA to the Prairie Provinces and because of the more general insights into the consequences of climate change provided by the ELA studies.

The remainder of this report will consist of an overview of the impacts of climate change on the major components of the aquatic ecosystem including: (1) hydrologic regime and fluvial geomorphology, (2) physico-chemical changes; (3) primary production; (4) zooplankton and; (5) higher trophic levels. The report will conclude with summary and recommendations to consider in any further investigation of the impacts of climate change.

Hydrologic regime and fluvial geomorphology

Alteration of the hydrologic cycle is one of the most obvious and immediate ways in which climate change will effect aquatic ecosystems (Lewis 1989; Chang *et al*. 1992). Climate changes will vary as a function of geography but are predicted to result to in an increased susceptibility to both summer drought and flooding in the Prairie Provinces (Wigley *et al*. 1980; Lewis 1989), these together with changes in runoff pattern have the potential to radically affect flow regime in streams and rivers. Unfortunately, the relationship between climate change and flow regime is complex and poorly understood (Carpenter *et al*. 1992) and while the frequency, intensity and extent of disturbance (e.g., scour, flood, drought, etc.) is known to be a critical determinant of community structure in lotic systems there is little consensus as to the specific consequences of such disturbance (Resh *et al*. 1988).

Increases in the frequency of extreme precipitation events will also affect fluvial geomorphology by increasing erosion and sediment transport. High magnitude floods will serve to widen stream channels, destroy riparian habitat, and alter aquatic habitat both at erosional sites and at downstream depositional sites. It is difficult to generalize as to the consequences of such disturbance to biota but fluvial geomorphological changes of this type may well serve to destroy critical habitat, restrict access to spawning tributaries, and may well affect general water quality (see below).

Changes in evapotranspiration patterns are perhaps the best studied impact of climate change on aquatic systems in the Prairie Provinces. Demuth (1994, 1995) has shown that changes in precipitation/evaporation patterns may result in a retreat of glaciers along the eastern slopes of the Continental Divide. Runoff from these glaciers is important to the maintenance of flow and habitat in the headwaters of several major prairie rivers. Contributions from glacial melt are particularly important in the transition from summer peak flows to base flow in these systems. Flow reductions resulting from decreases in glacier contribution may be further exacerbated by a downstream increase in water withdrawal for irrigation purposes.

In the ELA climate change has dramatically reduced flows in the small streams that feed those lakes. As a consequence several permanent first-order streams have become ephemeral and chemical exports from the small catchments to the lakes has been reduced. The many studies conducted by Schindler and his coworkers (see bibliography for a more complete list) have demonstrated that the relationships among the hydrology of these streams, patterns of chemical export and lake ecology are very complex and in many cases, counterintuitive. The details of these relationships will be discussed in greater depth below.

Changes in evapotranspiration will also have important consequences for the chemistry and ultimately biology of prairie wetlands (Larson 1995; LaBaugh *et al*. 1996; Poiani *et al*.1996) and saline lakes (Evans and Prepas 1996). Attempts to model these impacts have demonstrated that climate change not only affects the extent of wetlands but has major consequences for the chemical and vegetative dynamics within the wetlands (LaBaugh *et al*. 1996; Poiani *et al*.1996).

An understanding of climate impacts on the hydrologic cycle is thus a crucial first step in determining the consequences of climate change for aquatic ecosystems. The challenge for researchers is to more explicitly link climate change to the hydrologic cycle and then to link an understanding of the hydrologic cycle to the chemical and biotic structure and function of the ecosystem.

Physico-chemical changes

An increase in average air temperature will increase the annual energy and heat budgets of lakes in the Prairie Provinces, affecting mixing regimes, and increasing water temperature, evaporation rates, and the duration of the ice free season. In the ELA warmer temperatures were linked to clearer waters (partly because of a 50% reduction in DOC export from surrounding the catchment) and hence greater UVB penetration, deeper thermoclines and eutrophic zones, higher alkalinities, higher concentrations of base cations and nitrogen, lower concentrations of dissolved organic carbon, silica and phosphorous, increased water retention, and microbial sulfate reduction (Schindler *et al*. 1996a,b; also see papers by Bayley, Schindler and others in bibliography). As discussed By Schindler *et al.* (1996a), these changes are both complex and dramatic, were not predicted, were, in many cases, counterintuitive and all were a response to slight/moderate climate change. Furthermore, these impacts have major implications for the biological structure and function of these lakes (see below).

The studies conducted at the ELA serve not only to demonstrate the complexity of climate impact but also serve to demonstrate the inherit complexity of these systems. Even in those systems for which two to three decades of detailed data are available the full impact of warmer, drier weather is very difficult to quantify and virtually impossible to predict.

Though perhaps less well-studied closed-basin saline (> 1 g/liter total dissolved solids) lakes are common throughout the semiarid regions of the northern Great Plains and are known to be highly sensitive to changes in precipitation: evaporation ratios (Rawson and Moore 1944; Robarts et al. 1992; Laird *et al*. 1996; Evans and Prepas 1996). In a 12-year study of six saline lakes in Alberta Evans and Prepas (1996) demonstrated a climate induced increase in brine conductivity. This increase in conductivity was positively correlated with most major ions although the relative increases varied from lake to lake. Changes in conductivity also affected the structure of the phytoplankton community (see below).

In a similar sense, LaBaugh *et al*. (1996) have demonstrated that the chemistry of wetlands can be dramatically affected by extreme participation events (I.e., drought, deluge) and that the consequences extend well beyond the extreme events themselves. Chemical changes noted in this study included increased salinity during drought, and shifts in anion balance following inundation of vegetation zones.

As with the hydrologic cycle, climate change will obviously affect the physico-chemical nature of aquatic ecosystems throughout the prairies. However, the nature of such impacts are very much dependent on the precise nature and extent of climate change. In addition, the complex relationships involved present a considerable challenge to our ability to predict the net effect of any climate change.

Primary production

Changes in the timing and extent of runoff may affect both the rate of nutrient inflow and the total loading of nutrients to streams and rivers (and eventually to lakes) (Carpenter *et al*. 1992). In lotic systems, any run-off related change in nutrient loadings are likely to be manifest in changes in primary productivity. This is particularly true in the headwater reaches of many of the major prairie rivers where primary productivity is largely nutrient limited (Chambers 1996).

Similarly, lake productivity is generally correlated to watershed area and the nutrients exported by streams to the lake may have important consequences for primary productivity (Schindler *et al*. 1990; Bayley *et al*. 1992). A decrease in silica export to study lakes in the ELA may have been responsible for an observed decrease in diatoms (Schindler *et al*. 1996).

In saline lakes and wetlands Phytoplankton community structure and chlorophyll *a* (Chl *a*) has been shown to be correlated with salinity, possibly because of a salinity-linked shortage of nutrients other than phosphorous (Evans and Prepas 1996). Changes in planktonic diatom communities are so strongly linked to salinity and nutrient availability that they have been proposed as indicators of climate change in Moon Lake, North Dakota (Laird *et al*. 1996) and in the Yellowstone and Grand Teton National Parks (Kilham *et al*. 1996).

Sensitivity to temperature, salinity, general water chemistry, frequency and intensity of floods and droughts is also apparent in the macrophyte community. Climate changes that affect these variables can also be expected to alter the structure of the macrophyte community (Smith and Wallstein 1986).

Though not strictly a climate change issue, increases in UV-B radiation resulting from loss of stratospheric ozone has major implications for primary productivity in aquatic ecosystems and will be discussed in the general context of climate change.

UV-B radiation can inhibit photosynthesis in both oceans and lakes and in the Southern Ocean UV-B inhibition of biological processes has been detected at depths of up to 30m (Williamson 1995). Although the effects of UV-B on freshwater systems are generally less well understood some researchers have argued the inhibition of primary productivity by UV-B will result in decreased rates of carbon fixation, elevated levels of atmospheric CO_2 and an acceleration of global warming.

Bothwell *et al.* (1993, 1994) and DeNicola and Hoagland (1996) have demonstrated that higher levels of UV-B are capable of inhibiting photosynthesis in benthic diatoms in shallow freshwater systems. While Schindler *et al*. (1996) have demonstrated that climate-induced changes in the hydrologic cycle have reduced DOC export, increased water clarity and thereby increased UV-B penetration in the water column.

In a series of mesocosm experiments Bothwell *et al.* (1993, 1994) measured a higher diatom biomass in habitats exposed to UV-B than in controls. This counterintuitive result can be explained by the fact that larval chironomids (midges) that grazed on the diatoms were more sensitive to the UV-B radiation than were the diatoms themselves. The chironomids tended to avoid exposure to UV-B and thus did not graze on exposed diatoms. These experiments serve to illustrate that the ecosystem system consequences of exposure to UV-B cannot be assessed by examining a single trophic level.

Zooplankton

The zooplankton community can have considerable impact on phytoplankton communities on which they feed as well as on the higher trophic levels (e.g., fish) which rely on zooplankton as a major food source. Moore *et al*. (1995) have argued that climate change will have major consequences for zooplankton communities in so far as observed changes have already caused mid-summer water temperatures in many mid-latitude lakes to approach the thermal tolerance of a variety of zooplankton taxa. Higher summer water temperatures also result in smaller individuals, probably as a result of increased filtering and respiration rates coupled with a decrease in assimilation efficiency. In addition, climate change has also reduced the availability of cold water, oxygenated refugia that are important to zooplankton survival during the summer months.

Williamson (1995) has explored the potential impacts of harmful UV-B radiation on zooplankton communities and has identified a number of possible effects. In the first case, those zooplankton that cannot detect harmful UV-B radiation may be damaged by direct exposure in the same way that primary producers are. In the second case, smaller zooplankton, capable of avoiding harmful UV-B radiation may have to confine themselves to deeper strata to avoid radiation but by doing so expose themselves to a greater risk of predation by larger zooplankton and fish. This may not be a problem in eutrophic systems where UV-B rays are rapidly attenuated but will be an issue in oligotrophic systems in which UV-B rays can penetrate to a much greater depth. As discussed by Schindler *et al*. (1996a,b) changes in hydrology and DOC export may also contribute to a greater penetration of harmful UV-B radiation. Thirdly, UV-B effects on zooplankton predators and/or prey will be ultimately affect zooplankton through cascading trophic interactions.

Clearly, the effects of climate change on zooplankton are complex and can take direct or indirect forms. The importance of zooplankton in structuring prairie lake ecosystems is obvious and changes to this community are likely to have consequences at both higher and lower trophic levels.

Higher trophic levels

The direct consequence of climate change for trophic levels above zooplankton have not been well studied and will be particularly difficult to predict given their dependence on all of climate-induced changes in the physical and chemical processes occurring within the aquatic ecosystem as well changes affecting other trophic levels. Certain benthic macroinvertebrates (Bothwell *et al*. 1993,1994) and amphibians (Blaustein *et al*. 1994, 1995, 1996) are known to be sensitive to UV-B radiation and climate-induced changes in temperature and dissolved oxygen will undoubtedly affect developmental rates and survival in most aquatic invertebrates and macroinvertebrates.

Many species of fish, such as lake trout have fairly narrow temperature and dissolved oxygen requirements. This species and other cold stenotherms may be threatened by the loss of summer refugia that provide adequate conditions for these (Schindler *et al*. 1996). Carpenter *et al*. (1992) have argued that freshwater fish can be generally grouped as a function of their thermal tolerances into coldwater (e.g., Salmonidae), coolwater (e.g., Percidae) or warmwater (Centrarchidae and Cyprinidae) forms . All else being equal, increasing temperatures will allow each of these groups to extend their range into higher latitudes and may cause them to disappear from what is now the southern extent of their range.

The actual impacts of climate change on fish will however involve much more than thermal tolerance. Indeed, the fish community can be viewed as an integrator of most of the impacts discussed above. Changes in the hydrologic cycle are likely to affect the availability and quality of critical fish habitat. Climate-induced changes in the physico-chemical nature of prairie aquatic ecosystems may affect fish directly or indirectly, through impacts on their prey populations. Finally climate impacts at other trophic levels (e.g., primary producers, zooplankton, benthic macroinvertebrates) will obviously impact on the fish community.

SUMMARY AND RESEARCH RECOMMENDATIONS

Climate change and the impacts resulting from such change is a growing issue and one which will be the subject of ever increasing research efforts for the foreseeable future. While considerable effort has already been invested in attempts to monitor, model and predict climate change considerably less effort has been focused on investigations of the direct ecological impacts of climate change.

The challenge associated with determining the ecological impacts of climate change are daunting, the long-term data sets (such as that provided by the ELA study) required to investigate the impacts of climate change are rare, and the opportunities to undertake (or even continue) such studies are even rarer. It is possible to state that changes in temperature and precipitation in prairie aquatic systems will affect those ecosystem components sensitive to temperature and precipitation. However, such an observation is of little value. Attempts to be more predictive soon become mired in the complex nature of the relationships and the significant gaps in knowledge.

Future research on the impacts of climate change in aquatic systems in the Prairie Provinces should first focus on developing predictive models capable of linking hydrologic processes to climate change. This work has already been initiated but must be further developed. Prairie aquatic ecosystems are largely defined and driven by hydrologic issues such as drought, flooding, precipitation and evaporation. An understanding of how climate change will affect these processes is the first step in understanding the ultimate impacts of climate change on aquatic ecosystems in this region.

A second major obstacle to assessing the impacts of climate change is an incomplete understanding of the ecology of these systems. This is not a criticism of the research that has been done but a recognition of the complexity of these systems. Even after three decades of concentrated research in the ELA many basic ecological relationships remain unexplained and many of the observed changes would not have been predicted. For, example changes in the hydrologic cycle, reducing DOC export and increasing UV-B penetration was not an intuitively obvious outcome of climate change.

It is essential therefore that continued research into the basic ecology of these systems be supported and encouraged. At the same time, many of the basic ecological studies already conducted on these systems could provide useful insight into the potential consequences of climate change. These studies should be synthesized and reviewed in this context.

Finally, and as discussed above, climate change is but one element in a larger issue of environmental change and must be viewed in that context. No attempt to assess the impacts of climate change will be complete unless other forms of environmental change are accounted for. In the case of prairie aquatic ecosystems, stresses arising from the direct consequences of climate change are very likely to be exaggerated if other forms of environmental change (e.g., land use/cover changes) are not controlled

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APPENDIX H

LITERATURE REVIEW OF CLIMATE CHANGE AND WILDLIFE/BIODIVERSITY IN THE PRAIRIE PROVINCES

LITERATURE REVIEW OF CLIMATE CHANGE AND WILDLIFE/BIODIVERSITY IN THE PRAIRIE PROVINCES

C. L. Gratto-Trevor
Canadian Wildlife Service, Environment Canada
Saskatoon, Saskatchewan

INTRODUCTION

This paper summarizes the literature regarding potential and actual effects of climate change and climate variability on wildlife and biodiversity, primarily in the three Prairie Provinces. It also mentions present gaps in the literature, and suggests directions for further work. This covers most references to wildlife/biodiversity and climate change in this region. It is not an exhaustive list of all references describing ways in which climate directly and indirectly affects survival and productivity of prairie species. References are separated into the two major ecozones in the Prairie Provinces: prairie and boreal. Here 'wildlife' is defined as any vertebrate or invertebrate species found in the Prairie Provinces. 'Biodiversity' includes wildlife as well as plant species.

In general, papers on climate change and wildlife fall into two main categories: those that describe the use of particular species or taxonomic groups as 'indicator species' of environmental change, and those that attempt to predict future changes in community composition and structure, or species abundance, as a result of climate change. Some studies of indicator species involve the fossil record: either making assumptions about climate and environmental conditions in the past based on current requirements of species found as fossils (e.g. Elias 1991), or predicting future species assemblages based on fossils that existed under environmental conditions thought to be similar to those expected in the future. Other studies define current species known (or expected) to be highly sensitive to environmental change, and suggest that changes in distribution, abundance and/or behaviour of these species can be used as early biological indicators of climate change.
Generally, both indicator species studies and those examining potential effects of climate change on particular species or assemblages require fairly detailed information on abiotic and biotic factors affecting species distribution, survival and productivity.

PUBLISHED STUDIES

Prairie

Few studies directly involve effects of climate change on prairie wildlife or biodiversity. However, a number address responses of species to climate variability, notably drought. Aspects of climate change considered in prairie papers included direct effects of carbon dioxide on vegetation, earlier onset of spring, and drought (assumed to result from increased evaporation and evapotranspiration from higher summer temperatures, and potentially decreased precipitation, as suggested from most climate change scenarios for the prairies).

Effects on vegetation.

A simulation model of climate change on temperate grasslands suggested that temperature had less of an effect on annual production and decomposition than did precipitation, carbon dioxide level, or differences among native plant species (Hunt et al. 1991). Precipitation appeared to be the most important factor of all.

Growth of a number of prairie grass species was compared under conditions of increased carbon dioxide (Bazzaz and Fajer 1992). *Bromus tectorum* grew better than other species under those conditions. If this species increases in abundance under climate change, the authors suggested that this would lead to increases in the number and severity of wildfires on the Great Plains.

The effect of drought on biomass and species richness of grassland plants was measured in Minnesota (Tilman and El Haddi 1992). Decreases in above ground biomass, diversity and species richness were found, with local extinction of many rare species. Annuals were more likely to be lost from the study plots than were perennials, and their loss was not dependent on predrought abundance as was loss of perennial species. Little recovery had occurred even two years after the drought had ended.

Beaubien (1993, 1994) suggests that climate change and the earlier onset of spring can be tracked through changes in the flowering phenology of wildflowers in Alberta.

Effects on wildlife.

A considerable portion of the literature involves response of wetlands and waterfowl to drought. Climate explained more than 60% of the variation in number of wet basins throughout the Prairie Pothole Region of Canada and the United States, but Parkland wetlands were more sensitive to temperature than were Grassland wetlands (Larson 1995). The author noted that this may become important to nesting waterfowl if more birds shift to breed in the Parklands, as grasslands advance farther north. Waterfowl production is related not only to the number but also to the type of prairie wetlands (Diamond and Brace 1991), usually small seasonal and semipermanent ponds, which are likely to be affected by climate change. In North Dakota, for nonwaterfowl species as well, the greatest number of breeding bird species was found on seasonal and semipermanent wetlands (Kantrud and Stewart 1984). Highest overall bird densities were on semipermanent wetlands.

Long-term changes in wetland size and vegetation under differing environmental conditions (usually drought) were modeled for semipermanent North Dakota wetlands (Poiani and Johnson 1991, 1993, Poiani et al. 1996). As noted by LaBaugh et al. (1996), the response of wetlands to extremes in precipitation, resulting in shifts in major ion abundance and changing salinity-wetland water level relationships, is not usually considered in the relationship between major ion abundance and species composition. Changes in salinity and surrounding vegetation of wetlands has importance in determining not only foraging success (plants and insect prey of birds and other wildlife species), but also suitability of pond habitat (e.g. lack of cover desirable for foraging shorebird migrants, certain types of cover useful in hiding growing young of waterfowl and other species).

Initiation of breeding in prairie waterfowl is related to May temperatures and spring precipitation (Greenwood et al. 1995). Rates of renesting in waterfowl was particularly sensitive to drought conditions, presumably due to the absence of insect prey (Krapu et al. 1983). There are scattered studies involving other species. Variability in wetland conditions affected site tenacity of breeding shorebirds differently for each species in Saskatchewan (Colwell 1991). Species richness, diversity, and density of grassland songbirds declined in North Dakota during drought (George et al. 1992). Great variability in response existed among different species. In some, nesting success declined due to nest abandonment, presumably due to a lack of insect prey. Larson (1994) clearly summarizes potential effects of climate change (including increased carbon dioxide, UV-B, and temperature, and decreased precipitation) on birds breeding in the northern Great Plains. She suggested that the probable decreases in plant nutritional value, changes in timing of insect emergence, decreased number and higher salinity of wetlands would result in fewer birds. However, this effect might be mitigated by possible increases in drought resistance and more efficient water use by plants, the longer growing season, and increased plant biomass.

Johnson (1993) noted that insects (important as food of vertebrates, pollinators, and agricultural pests) were strongly influenced by weather and vegetation. He suggested that changes in insect species assemblages would be a good bioindicator of climate change. He also noted that some agricultural pests would be likely to increase with climate change, such as adult grasshoppers in Alberta, since their numbers decrease with increased rainfall (Johnson and Worobec 1988).

Few mammal studies were noted. Simulated drought conditions depressed captive vole reproduction (Nelson et al. 1989). As a description of how climate could affect vertebrate species by initiating structural changes in the abiotic, rather than biotic environment, Stokes and Slade (1994) studied the use of cracks in the soil of the Great Plains as refuges of small mammals. Voles used cracks less than deer mice, so might be relatively less protected from predators when conditions are drier.

Declines in amphibian abundance have been noted globally, as well as in western North America (Blaustein and Wake 1990). Suggested local causes include acidification of ponds, introduced predators (fish and bullfrogs), and pesticides. There may be synergistic effects between local factors and long-term low level exposure to increases in UV radiation and temperature from global warming. Hatching success in some species of salamanders and frogs was significantly higher for those shielded from UV-B than those not shielded (Blaustein et al. 1995, 1996). UV-B radiation is probably most detrimental in species that lay eggs in open shallow water, and have a poor capacity to repair UV-damaged DNA (low photolyase activity).

The previous studies primarily involved local prairie breeders. Species migrating through the prairies can also be greatly affected by climate change. The effects of drought on shorebirds migrating through Kansas was addressed (Castro et al. 1990). With more wetlands drained directly due to agriculture, and irrigation resulting in greatly decreased water in the aquifer of some areas, fewer alternative wetlands for staging shorebirds exist in drought years in the interior of North America. Wittrock and Wheaton (1989), examining the impact of drought on Canadian prairie birds, noted that wetland basins, once dry, are often then cultivated and lost even if water conditions improve in future years. They also noted an apparent increase in avian cholera in waterfowl during drought, presumably the result of concentrating birds in fewer extant wetlands, and lowered resistance to disease due to stress and poor foraging opportunities. Productivity of arctic nesting snow geese declined in prairie drought years, as females obtained less stored nutrients on the prairies for later egg production (Davies and Cooke 1983).

Global warming will not be uniform across regions. If some areas warm more or faster than others, this indirectly may have severe effects on migrants between those areas. Arctic shorebirds are long-distance migrants, dependent on food resources elsewhere at specific times of the year. If the timing of food flushes elsewhere (e.g. horseshoe crab eggs at Delaware Bay) changes more slowly (as expected) than invertebrate regimes in the arctic, the birds may not be able to migrate early enough to hatch eggs before peak insect hatch (Lester and Myers 1991).

Foraging habitat at staging areas may also be affected by climate change. For example, coastal staging areas used by shorebird migrants may be flooded by increases in sea level, making these sites unavailable to the birds.

Boreal

Virtually all references to the effects of climate change on the Canadian boreal region discuss either the potential effects of changing boreal vegetation on climate, or potential effects of changing climate on vegetation. These topics are undoubtedly covered in Wheaton's forestry section, so will only be briefly discussed below. Almost none discuss wildlife except to note potential changes in the frequency of forest insect pest outbreaks.

Feedback effects on climate

Changes in boreal habitat could have major feedback effects on climate in several ways. The presence of trees mask the high reflectance of snow, leading to warmer winter temperatures than if trees were absent (Bonan et al. 1992). Deforestation leads to decreases in temperature, even beyond the deforested area. Changes in species composition, as well as spatial distribution of vegetation, can result in both positive and negative feedbacks on climate (Price and Apps 1995). Other feedback mechanisms on climate from changes in the boreal ecosystem include carbon sequestering and methane emissions (Wheaton and Wittrock 1994). Formation of new ponds and flooding of existing peatlands will result in changes in the carbon pool and methane production, acting as a positive feedback on greenhouse gases (Bridgham et al. 1995). Fire is expected to increase with climate change in the boreal forest. This will result in an increased release of carbon dioxide during the fire, and higher decomposition rates for decades later will continue to release more carbon dioxide (Wein and deGroot 1996). Changes in wildlife abundance can also have a large effect. In a Minnesota study, increases in beaver populations results in almost a four-fold increase in methane emission from peat wetlands (Bridgham et al. 1995).

Effects on vegetation

Sanderburgh et al. (1987) reviewed potential effects of increased carbon dioxide and climate change on forest management in the United

States. They expected changes in rates of photosynthesis, water use efficiency, and nitrogen fixation, which would affect tree growth rates and production, and influence the distribution of tree species. Increased extremes in temperature, rainfall and wind would likely result in increased loss of timber to fire and pests. They noted that changes in climate would occur much faster than in previous times.

Singh and Wheaton (1991) discussed sensitivity of the boreal forest in the western Canadian interior to global warming. Proposed increases in water use efficiency would vary among species, depending on the magnitude of stomatal closure and species physiology. Therefore ecosystem characteristics most likely to be modified by global warming include natural succession, nutrient cycling, grazing and browsing, and competitive interactions. Soil moisture is expected to decrease, and fire, insect and disease infestations increase. If moisture becomes limiting, forest diebacks might occur. Because of the current and expected rate of global warming, tree seed dispersal is not expected to keep up with a potential range shift of 100-150 km for each one degree Celsius increase in temperature in North America. The authors state that this will be disastrous for forest production without massive human intervention in reseeding appropriate species.

Advance of the treeline in the north and retreat in the south has been calculated in several studies. Payette and Lavoie (1994) examined changes in the arctic treeline historically from soil pollen samples. In Sargent's (1988) model of the redistribution of the Canadian boreal forest under climate change, the area climatically suitable for boreal forests advanced by 70,000,000 ha at the northern edge (due to increased winter temperatures) and retreated by 170,000,000 ha from the southern edge (due to lack of moisture). According to Wheaton et al. (1989), the northern boundary is expected to advance by 100-700 km, and the southern boundary retreat by 250-900 km. Many studies discussed the effects of increased fire (Flannigan and Wagner 1991, Wein and Landhausser 1994, Wein and deGroot 1996, Fosberg et al. 1996) on tree species composition and abundance. Decrease in soil moisture was also expected to result in changes in dominance of tree species (Kurtz and Sampson 1991, Lenihan and Neilson 1995). Since changes in moisture regimes are expected to be greatest at patch edges, increased fragmentation of the boreal forest may accelerate soil moisture loss (Hogg 1994, Hogg and Hirtle 1995). With increased average temperature, tree insect pest outbreaks and tree pathogens are expected to increase as well (Fleming and Volney 1995). If trees are moisture stressed, they may be more susceptible to pathogens and grazing (Wheaton 1992).

As noted earlier, the speed of climate change is expected to outstrip the ability of tree migration in response. In addition, current landscape practices have created barriers to plant migration (Kurtz and Sampson 1991). In Minnesota, Davis (1990) listed several factors adding to limited dispersal of tree species, including increased deer browsing (limiting reproduction), a decreased seed source due to logging, and less old growth to produce dead logs that protect seedling growth. She noted that dispersal would be even more of a problem for wind-dispersed herbs. Since humans can plant economically useful tree species in disturbed habitats, Davis (1989) expected natural areas to be most affected by lags in vegetation responses to greenhouse warming.

In North American mountain habitats, Romme and Turner (1991) examined the implications of global change for biogeographic patterns in the Greater Yellowstone Ecosystem. They concluded that the upper and lower timberlines appeared particularly sensitive to climate change, and that, in all the scenarios they tested, amount of alpine vegetation decreased. Changes in fire regimes had consequences for the extent and age class distribution of forest communities.

Effects on wildlife or biodiversity

There is very little mention of potential effects of climate change on wildlife in western boreal forests. Singh and Wheaton (1991) note that global warming is likely to affect wildlife habitat, and that there is a potential threat to the survival of species confined to parks and reserves that could become habitat islands. In New Hampshire, Rodenhouse (1992) stated that songbirds could be greatly affected by climate change since most species are insectivorous, and because changes in forest tree species composition might result in changes in bird habitat.

Montane mammals were used to model extinctions due to global climate change in the western United States (McDonald and Brown 1992). The model was based on the species-area relationship, with area determined by presumed latitudinal changes in vegetation type. An increase of three degrees Celsius was predicted to result in the loss of 9-62% of species inhabiting each mountain range, and extinction of 3 of 14 species throughout the region. The authors concluded that they could make highly plausible predictions about susceptibility of species to extinction without detailed information about their population biology, and that species most threatened are those restricted to natural habitat 'islands' such as mountain tops, and those in biological reserves.

The effect of drought on birds was studied in subalpine areas of northern Utah (Smith 1982). The number of species decreased most in aspen areas. Densities of singing males decreased, as did numbers of insectivorous birds, and insectivorous hummingbirds disappeared. The number of granivorous finch species increased. The author related this to changes in food resources, and concluded that avian communities in deciduous vegetation may be more affected by drought than those in coniferous vegetation. Numbers of birds in alpine meadows changed very little. On high mountain slopes in western Colorado, the Uncompahgre fritillary butterfly declined in number and went extinct during the hot dry summers of the late 1980's (Mlot 1991).

RESEARCH NEEDS

Prairie

Wildlife expected to be most affected by climate change in this region are species tied to semipermanent or seasonal wetlands. Amphibians in particular appear to be at risk, especially given their worldwide global declines (Wyman 1991). Studies examining the synergistic effects of UV-B radiation, water chemistry, and agricultural chemicals appear to be lacking for Canadian prairie amphibians. Ways in which climate affects waterfowl production are well known, but we need more information on factors affecting productivity and survival of nongame species. Due to the need of many shorebird species for shallow wetlands that are highly susceptible to climate change, this group is also at risk. The potential fate of semipermanent and seasonal wetlands under a changed climate needs to be addressed. If sufficient information exists on individual species (or species assemblages) and climate, species interactions, abundances and so on, lists of 'risk assessment' could be created for groups of animals and plants. For example, although the Long-billed Curlew is currently high on a list of birds potentially at risk of extinction (due to their decreasing habitat and low population numbers), I would expect this species to benefit from climate change, as its preferred habitat is dry, heavily grazed grassland.

Boreal

Although considerable literature has been published on potential effects of climate change on commercial tree species, very little work appears to have considered the fate of understory plants or wildlife. Ironically, 76% of Canadian terrestrial mammals and 60% of Canadian breeding bird species are forest dwelling (cited in Boyle 1991). Since they are primarily insectivores, boreal nesting songbirds would be expected to be greatly affected by changes in forest composition, presumably with considerable variability among songbird species. This must be addressed in particular, and lists of 'risk assessment' created for other boreal species as well.

Summary

Climate change can affect wildlife and biodiversity in many ways (McAllister and Dalton 1992). Effects may be direct, whether immediate or delayed (e.g. lethal temperatures vs. heat stress), or indirect. Indirect effects include changes in food abundance or availability, habitat loss or degradation, and changes in predation rates, competitive interactions, parasites and disease. 'Cascade' effects may result in massive changes to the ecosystem if keystone species are affected. Dispersal may be a limiting factor, either in innate ability to disperse, lack of source populations, or landscape barriers to dispersal. Particularly for migrants, changes in timing of food abundance at staging versus breeding areas could be very important to survival (Dolman and Sutherland 1994).

Climate change can have very different effects on even taxonomically similar species. In order to predict responses of a species or species assemblage to climate change, fairly detailed information on biotic and abiotic factors affecting species reproduction and survival are necessary. Studies attempting to predict effects of climate change on wildlife must take into account not only species specific responses to climate, but also changes in habitat and abundance of other species, dispersal opportunities, and most particularly, potential changes in land use activities (Myers 1992). For example, increased incidence of drought on the prairies will not only result in drying of wetlands, but dry ponds are often cultivated and so lost even after the end of the drought period. Irrigation may become common in areas that have historically used dry land farming, potentially reducing water in aquifers and wetlands. Increases in insect outbreaks might benefit songbirds in the boreal forest, but more intensive insect spraying might eliminate any advantage. An advance of grassland habitat northwards could extend the range of grassland habitat, but intensification of agriculture in that region could offset any gain. Anthropogenic changes in land use can provide great barriers to species dispersal into appropriate climatic zones.

ACKNOWLEDGMENTS

Enid Cumming collected almost all of the references cited above, and I am very grateful for her help. Too many people to list separately supplied references or sources, but I would like to express my appreciation to all of them.

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APPENDIX I

PROXY RECORDS OF POSTGLACIAL CLIMATE IN THE CANADIAN PRAIRIE PROVINCES

PROXY RECORDS OF POSTGLACIAL CLIMATE IN THE CANADIAN PRAIRIE PROVINCES: A GUIDE TO THE LITERATURE AND CURRENT RESEARCH

D.J. (Dave) Sauchyn, Professor
Department of Geography
University of Regina

May, 1997

PREFACE

This report summarizes published and current studies on the postglacial climates of the Canadian prairie provinces as reconstructed from proxy records. The objective is to describe the database of proxy paleoclimatic data, categorize the previous and current research topically and geographically, and identify gaps in our current understanding of postglacial climatic change and variability. The companion bibliography lists more than 400 studies conducted in the prairie provinces and at nearby sites in British Columbia and the northern US plains.

For many reasons outlined below, a complete synthesis of the results of these studies is well beyond the scope this report and the expertise of a single author. The lack of previous attempts at synthesis is the best indication that it is probably not even possible without a better understanding of the response of natural systems to climatic forcing. This report does, however, review climatic reconstructions from key sites, those which have produced the longest, most detailed and best controlled records. This is the approach taken by the few other summaries of paleoenvironmental research. These other overviews have concentrated on a single proxy, such as pollen (Liu, 1980; Beaudoin, 1993) and tree rings (Luckman and Innes, 1991), a specific time frame, such as the climatic optimum (Vance et al., 1995), or part of one province (Beaudoin, submitted). This report, on the other hand, encompasses all the proxies, geological, biological and historical, including tree rings and glaciers, and the entire postglacial period. Thus the emphasis necessarily is on summary rather than synthesis, and on the factors that constrain the use and interpretation of each type of proxy record.

Paleoenvironmental research is collaborative and multidisciplinary, since it involves the sampling, analysis and interpretation of all the remains of past environments: soils, sediments, flora and fauna. To assume understanding of all these proxies is ambitious and even arrogant. Thus I have relied heavily on colleagues for the preparation of this report. I received e-mail, reprints and advice from the leading authorities on the paleoenvironments of the Canadian plains: Alwynne Beaudoin, Provincial Museum of Alberta; Celina Campbell, University of Alberta; Mike Dumuth, National Hydrology Research Centre; Bill Last, University of Manitoba; Peter Leavitt, University of Regina; Don Lemmen, Geological Survey of Canada (Calgary); Erik Nielson, Manitoba Energy and Mines; Bob Vance, Geological Survey of Canada (Ottawa); and Mary Vetter, Luther College (University of Regina). Hopefully my biases, and lack of understanding in certain areas, have not done injustice to the work of my colleagues. An emphasis on Holocene stratigraphy and tree rings reflects the author's interests and some expertise. The section on biological proxies is simply a compilation of the work of colleagues. Also, it is entirely possible that I have overlooked some current research, particularly by graduate students. This report also reflects a focus on the plains region of the prairie provinces, although there was a conscious attempt to incorporate literature and records from the northern forests and Rocky Mountains. The plains region, however, is where the impacts of climate change and variability have the most profound influence on human activities, principally agriculture.

INTRODUCTION

There is little need to make a case here for better understanding of climatic variability and change. The past and potential impacts on natural resources and human activities are the subject of a large body of recent literature (*e.g.* Williams et al*.,* 1988; Wilhite and Wood, 1995). The social costs are large and thus climatic change and variability are among the most serious social and environmental issues at the end of the second millennium. In the prairie provinces, they affect various resource industries (forestry, energy, tourism), although most of the concern and attention is focused on agriculture (Williams et al., 1988; Schweger and Hooey, 1991). The viability of prairie agriculture depends very much on the adjustment of land use and production systems to climatic variability and change. There adjustment is perpetual, although historically prairie agriculture has succeeded in adapting to climatic variability (Hill and Vaisey, 1995: 52). More than anywhere else in Canada, understanding of the long-term variation in climate benefits the sustainable management of land and water resources. Studies of paleohydrology and paleoprecipitation often are linked to the reconstruction of drought frequency. Nemanishen (1995: 6) suggested that "During the seven year period, 1984-1990, the drought years invariably found all three levels of government unprepared. ... Millions of dollars could have been saved and more timely response provided if drought forecasts had been available." Farmers and scientists cannot be certain that climatic variability in future decades will not exceed the extremes of weather observed in this century. Since our instrumental climatic records are relatively short, generally less than 100 years, an alternative source of climatic data is required to provide a broader perspective on climatic variability and change.

This report is an overview of research on postglacial climatic change and variability as reconstructed from proxy data collected within the boundaries of the Canadian prairie provinces and nearby in the BC Rockies and northern Montana and North Dakota. Our understanding of climatic variability and change over geologic time is based on the sampling, analysis and interpretation of the remnants of past (paleo) environments. Large amounts of proxy paleoclimatic data have been derived from the relative and absolute abundance of faunal and floral remains, soil and lake sediment mineralogy, lacustrine (lake) and terrestrial lithostratigraphy, tree rings, and the stable isotope composition of various biological and geological archives (Bradley, 1985; Warner, 1990; Delcourt and Delcourt, 1991; Goudie, 1992). The most valid reconstructions of past environments are based on multiple parameters from one site, for example Harris Lake, (Sauchyn, 1990; Sauchyn and Sauchyn, 1991; Last and Sauchyn, 1993; Wilson et al., 1997) or even better from a single sample or core (Vance et al., in press). The multiproxy approach lends greater confidence to paleoclimatic reconstructions and permits comparison of the different signals preserved by the various proxies.

This report has four parts. This introduction will continue with an overview of paleoclimatic research in the Canadian prairies. The major section is the description and discussion of the various proxy indicators of climate, including the characteristics and limitations and the use of each type of proxy in the Canadian interior. Next is an overview of paleoenvironmental research from the western Cypress Hills, where the author and his collaborators have explored various proxies of postglacial climatic variability and change. This section is intended as an illustration of the environmental history that can be derived from a specific area. The concluding section identifies knowledge gaps and recommends directions for future research. The structure of this report also reflects a distinction between long (millennial) proxy records of relatively low resolution (decadal to centennial) versus shorter (centennial) records of annual resolution. This dichotomy generally corresponds to the reconstruction of climatic change, a significant departure from previous average conditions, and climatic variability, periodic fluctuation of atmospheric conditions (*e.g.*

drought, early frosts, major storms) (Environment Canada, 1995).

Since annually laminated lake sediments (varves) have not been described from the Canadian prairies, only tree rings and historical records provide the resolution necessary to identify climatic variability. Lake sediment records, on the other hand, usually have sufficient length to encompass climatic change, although long tree ring chronologies also can contain some lower frequency climatic variation. The studies described here span the postglacial period, but the focus is on the late-Holocene, that is, the most recent few millennia of earth history. The more recent records tend to have the highest resolution and thus provide the best opportunity to reconstruct climatic variability. Also, historical data may be available to corroborate inferences from recent proxy data. For example, verification of unusual years, seasons or events sometimes can be found in the diaries and journals of fur traders and explorers (*e.g.* Palliser, 1859).

Despite renewed interest in the Holocene paleolimnology of the southern Canadian Interior Plains (Vance et al*.*, 1995; Vance and Mathewes, 1994; Vance and Last, 1994; Wilson et al*.,* 1996), most of the existing proxy data are from the mountains-foothills and northern forest with their relative abundance of lake and trees. Many paleoclimatic study sites are located in ecotonal areas, transitional between major vegetation types. These records are particularly sensitive indicators of vegetation boundary shifts. The homogenous structure of the northern boreal forest, and thus perceived lack of sensitivity, has discouraged paleoecological research, however some lakes and recent studies of peatlands (Zoltai and Vitt, 1990) have yielded valuable results.

The subhumid to semiarid grasslands has been the region of least investigation, reflecting mainly the lack of trees and lakes, both presently and in the past. The lake records tend to be short and discontinuous. Most lakes are shallow and dry up during prolonged drought. Wind erosion of dry lake bottoms removes parts of the sedimentary record. Soil forming processes or the diagenesis of salts can create indurated (hard) layers that are difficult to penetrate with lake coring equipment (Teller and Last, 1982). Even where the lake sediments survive exposure to weather, the biotic remains can be destroyed or degraded by oxidation, especially with the wetting and drying of a lake bed.

The bibliography that accompanies this report cites more than 400 paleoclimatic studies from the Canadian prairies and nearby sites in BC and northern Montana and North Dakota. A complete synthesis of the results of these studies is well beyond the scope of this report and the expertise of a single author. In fact, a synthesis likely is not possible, without much better understanding of the responses of natural systems and processes, and individual proxy parameters to climatic change and variability. Then there is the sheer volume of data and the unique limitations of each proxy as discussed below. Furthermore, there are the following universal factors.

Location: Much environmental change is time-transgressive, with local and regional responses at varying times and rates. With the retreat of the late Wisconsinan Laurentide ice sheet across the Canadian plains, environmental changes, including the shifting of vegetation boundaries and the mid-Holocene hypsithermal (ultimate warm period), transgressed thousands of years, beginning and peaking at progressively later dates from southwest to northeast across the continental interior (Vance et al., 1995). Furthermore, the timing and strength of responses to climatic forcing vary geographically according to elevation and the prevailing water balance and vegetation. For example, lake sediments tend to house detailed records of climate during dry periods, when lakes are low and sensitive, while high water levels tend to buffer the impacts of temperature and precipitation fluctuations. Thus indications of climatic change tend to appear at different times according to both location and type of proxy.

Resolution: Temporal resolution varies among proxy records according to the time span represented by individual samples and the spacing between them, as dictated by the size of the sampled population (*i.e*. potential number of samples). This, in turn, depends on the amount of material collected (e.g. length of a sediment core), and the laboratory procedures for the extraction of proxy data. Sedimentation in the typically shallow and saline prairie lakes is affected by precipitation of salts, resuspension of sediments on windy days, and periodic desiccation of the lake basin. Therefore, a single sample of lake sediment core represents material accumulated over various amounts of time.

The proxies: Each proxy is a signal of a particular scale and aspect of climate, from the response of terrestrial (upland) vegetation to regional temperature and precipitation over many years to the sensitivity of aquatic organisms to lake salinity, and carbonate mineralogy to lake water chemistry and temperature.

Non-climatic controls: Other external factors, besides climate, and internal controls influence the behavior of natural systems. The response to climate normally is indirect and non-linear. It is filtered through the various biophysical processes (e.g. competition, succession, eutrophication, weathering) via which ecosystems evolve. The non-linear response includes thresholds, causing change which is disproportional to the magnitude of the forcing. Significant variation in proxy data can thus reflect events in the history of natural systems that correspond to internal thresholds or to events that are indirectly or non-climatic.

Chronological control: Establishing the timing of climatic changes and resolving climatic variability depend entirely on chronological control. Quaternary chronology is based largely on radiocarbon dating augmented with recognizable chronostratigraphic markers: paleosols formed over large areas in response to regional climatic amelioration and volcanic ash in mountains and adjacent plains. Indicator and signatures rings are similar chronologic markers in tree ring series. In Alberta and southwestern Saskatchewan, the most common and useful chronostratigraphic markers are the mid-Holocene Mazama ash and an early-Holocene paleosol (Valentine et al., 1987 ; Waters and Rutter, 1984).

Only tree rings and varves (annual laminated sediments) can be assigned to individual years. Even these often represent floating chronologies, which must be dated by other means or correlated (cross-dated) with modern samples or strata to obtain absolute dates. Measurement of the radioactivity and, more recently mass, of carbon-14 has been the basis for dating Quaternary sediments for the past 50 years. A few paleoecological studies from the Canadian plains (e.g. Hansen, 1949, 1952) pre-date the widespread use of radiocarbon dating, and thus these chronologies are speculative and based mainly on sediment stratigraphy. The error term (+/-) with a conventional radiocarbon date reflects the statistical (sampling) nature of the laboratory procedure. With the use of accelerator mass spectrometry (AMS) to measure the mass of carbon-14, the size of the error term has been significantly reduced. The real advance of AMS dating, however, is the sample size, just several grams of organic material, such as fragments of plant and animal remains. The validity of conventional radiocarbon dates has been a weakness of Quaternary chronology, because they usually represent the age of larger bulk soil or sediment samples, which can include radiogenically dead carbon that predates the date of sedimentation or soil formation by many thousands or even millions of years. This problem has been acute in the mountains and southern Interior Plains, given the various sources of older carbon: calcareous and marine bedrock, coal, hard groundwater. Beaudoin (1993: 97) observed that “Given the problems of chronologic control and the fact that these records were produced over a 40 year interval, integrating them and producing a comprehensive regional pattern of postglacial environmental change in Alberta is a formidable challenge”. Even though there have been more than 400 paleoenvironmental studies, relatively few represent long, high resolution and chronologically controlled records. In the next section, a few of the better paleoecological records are described.

PALEOLIMNOLOGY AND PALEOECOLOGY

The study of lakes and ecosystems over geologic time is based primarily on lacustrine sedimentology and the biota (pollen, spores, plant macrofossils, diatoms, ostracodes, *etc*.) preserved under anaerobic (saturated) conditions. Thus nearly all paleoecology is based on the analysis of lake sediments. The few exceptions are studies of plant remains in buried soils (e.g. Schweger, 1972) and peatlands (Zoltai and Vitt, 1990). The dominant and traditional biological proxy has been plant pollen. Palynology assumes that the percentage of pollen grains preserved for each taxa is a surrogate for the number of parent plants and thus the vegetation community at a site (MacDonald, 1990). These relative percentages are biased by the differential production and preservation of pollen, the mechanisms and distances of dispersal, and redistribution by wind and water. Interpretation of pollen spectra is based on the climatic limits of one or more indicator species, or in some cases quantitative transfer functions (Vance, 1986).

Palynology was so dominant for so many years, that it has influenced our perception of climatic change. Pollen is mostly a record of upland terrestrial vegetation, which naturally is of interest to paleobotantists, but also to archaeologists, as aboriginal populations were subject to shifting vegetation zones (Beaudoin, 1993). These shifts occurred mostly in response to climatic change, but are governed by the rates of ecological processes (e.g. migration, succession, competition). The lag between climatic and vegetation change is even more pronounced where suitable substrate (soil) must first form to support the vascular plants which produce the best preserved pollen grains. Differential preservation and dispersal among plant species also is problematic for the interpretation of pollen diagrams. For example, *Pinus* pollen is generally over-represented in modern pollen samples from the northern Great Plains, and thus relative percentages must reach at least 15-20 percent before pine can be assumed to occur in a forested region (Mott, 1969, 1973; Ritchie, 1976; MacDonald and Cwynar, 1985; MacDonald and Ritchie, 1986). The lack of differentiation among *Graminea* (grass) pollen, limits the use of palynology in the southern Interior Plains. Despite these constraints, palynology has been a powerful method of paleoenvironmental reconstruction, given the ubiquity of plant pollen. A major advantage is the widespread use and thus availability of pollen records for many sites worldwide.

Relative to other biological proxies, however, pollen data are relatively crude, since they represent regional environmental changes of sufficient magnitude to cause shifting of vegetation zones. Recent lake sediment studies therefore have focused on other biota which respond to subtle variations in limnological systems. Diatoms and ostracodes are aquatic organisms with short life cycles that are sensitive to the local conditions such as water salinity, temperature and depth (Delorme, 1969; Forester et al*.,* 1989; Smol et al*.,* 1991, 1995). Thus these proxies are a record of local conditions, both in time and space. Sampling location becomes a consideration, since these populations will vary within a lake. Plant macrofossils (mostly seeds) stored in near-shore sediments are evidence of local shoreline and aquatic vegetation (Vance et al., 1993).

Ostracodes are a group of bivalved Crustaceans. They are found in virtually all oxic aquatic environments (Forester et al., 1987). Of the approximately 35,000 taxa described, 2000 are freshwater species (Loffler, 1986), 420 of which are known to occur in North America (Delorme, 1991). Several adaptations to freshwater prevent local extinction during temporarily unfavourable conditions. Torpidity (dormancy) allows ostracodes, with a life cycle of more than one year, to survive drought or other short-term stresses (Delorme and Donald, 1969). The eggs can withstand freezing and desiccation, remain viable after drying for up to 30 years, and are rapidly dispersed by wind, waterfowl and other animals (Delorme, 1991). The resistive egg stage allows freshwater ostracodes to survive temporary loss of their aquatic habitat. The length of life cycles varies with the permanence of water bodies; the more stable the habitat the longer the life cycle (up to six to 24 months) in large lakes, although the usual life span is from a few weeks to seven or eight months (Pennak, 1978). Well defined biogeographic ranges (Forester et al*.,* 1989), rapid means of dispersal (Delorme, 1969) and high fecundity (Kaesler, 1983) ensure that an ostracode assemblage reflects immediate conditions, spatially and temporally. Their relatively easy identification, and density and diversity in virtually all lacustrine sediments, further favours ostracodes as paleoecological indicators (Hazel, 1988).

Diatoms are a widely-distributed group of microscopic, unicellular algae (Moser, MacDonald and Smol, 1996). They are usually well preserved in sedimentary deposits, by virtue of siliceous cell walls. The size, shape and sculpturing of the cell walls vary among taxa. These diagnostic features and their sensitivity to various environmental variables, make the type and abundance of diatoms excellent proxy data for the reconstruction of hydrology and climate. Although biological methods of paleoenvironmental reconstruction share a similar methodology (Birks and Birks, 1980), the use of analogue parameters, with ostracodes and diatoms in particular, provide more specific information on the nature of environmental changes (Forester et al., 1987). Quantitative estimates of paleo-parameters are inferred from an understanding of autecology, the environments that support modern communities (analogues). Delorme (1969, 1971) collected detailed autecological data for freshwater ostracodes from over 7000 sites in the Canadian interior, mostly the prairie provinces. The most relevant autecological dataset for diatoms is from 111 saline lakes in the subhumid interior of British Columbia (Wilson et al*.,* 1994). The sensitivity of ostracodes and diatoms to local water conditions (salinity, temperature, turbidity) enables the application of modern analogues to paleolimnology, with greater confidence than, for example, transfer functions based on plant pollen (Vance, 1986). Fossil assemblages with no modern analogue are problematic for the interpretation of paleoclimate.

Proxy records

Pollen studies in the prairie provinces have led to the acceptance of a spruce-dominated postglacial forest (Kupsch, 1960; Ritchie and deVries, 1964; Ritchie and Lichti-Federovich, 1968; Ritchie, 1969, 1987; Terasmae, 1973; Barnosky et al., 1987), fluctuation in alpine treeline (Kearney and Luckman, 1983a, 1983b, 1987; Beaudoin and King, 1990), mid-Holocene phytoinstability (Schweger and Hickman, 1989; Sauchyn and Sauchyn, 1991; Vance et al., 1992) and shifting of the prairie ecozones (Mott, 1973; Lichti-Federovich, 1970; Ritchie, 1987). The postglacial forest migrated northward with the retreat of the Laurentide ice sheet and became established as the boreal forest. The northward spread of white spruce (*Picea glauca*) from a southern refugium (Ritchie and MacDonald, 1986) and the "early version of the boreal forest that occupied a wide belt across the center of the continent from 14,000 to 12,000 yr BP" (before present) (Ritchie, 1987) provides a reasonable explanation for the origin of *Picea glauca* in the Cypress Hills. MacDonald and Cwynar (1985) concluded that *Pinus contorta* arrived in southern Alberta sometime around 12,200-10,400 yr BP. The *Picea glauca* (white spruce) and *Pinus contorta* (lodgepole pine) forest of the Cypress Hills may be a remnant of this early postglacial forest, as hypothesized by Thompson and Kuijt (1976) for conifers in the Sweetgrass Hills of Montana. Pollen evidence (Sauchyn and Sauchyn, 1991) suggests that *Picea glauca* and *Pinus contorta* were not eliminated from the Cypress Hills during the mid-Holocene warming, but rather small populations survived in small, isolated stands within a *Populus* forest-grassland matrix.

The pollen record from Lofty Lake (Lichti-Federovich, 1970) has been, for several decades, the source of the standard vegetation history of the Canadian interior. It shows changes from sage and poplar, unlike any present prairie plant community, to spruce forest, to a birch and poplar woodland within about 2,000 years of the retreat of the Laurentide ice sheet. Between about 7,500-5,000 yr BP, grass and sage pollen increased relative to tree pollen, suggesting the extension of grassland northward by as much as 80 km. Pollen data from southwestern Alberta suggests a *Pinus flexilis* parkland and warm dry climate (MacDonald, 1989). Spruce and pine pollen subsequently increased with a return to wetter conditions after about 6,000 yr BP. Lofty Lake is in the southern boreal forest - parkland transition in east-central Alberta.

Other lakes in this region and in the forested foothills (e.g. Moore, Fairfax, Wabamun and Cooking lakes) have been intensively studied by researchers from the University of Alberta (Hickman, 1987; Hickman et al*.,* 1984, 1990; Anderson et al., 1989; Schweger and Hickman, 1989; Hickman and Schweger, 1989,1991a, 1991b, 1993, 1996). This research indicates arid conditions during 12,000-9000 yr BP. The establishment of grassland vegetation may have been delayed by the cold event known as the Younger Dryas. During 9000-6000 yr BP, water levels dropped as indicated by the abundance of *Ruppia,* which can tolerate very saline conditions (Schweger and Hickman, 1989). Diatom records from these lakes suggests low and fluctuating water levels. In the Rocky Mountains, the warm and dry hypsithermal resulted in the migration of trees upslope and grassland into the valley bottoms (Luckman and Kearney, 1986). About 100 m above present treeline, wood from spruce trees has been found buried in peat. This wood has radiocarbon ages between 8800 and 7900 years BP.

The pollen records from four lakes in central Saskatchewan (Mott, 1967, 1973) show that the postglacial spruce-dominated forest was succeeded by grassland that may have migrated as far north as Prince Albert during the hypsithermal. Increased shrub and tree pollen marked the return to moister conditions, however these records were lacking in chronological control. More recently, Yansa (1995) examined plant macrofossils from a small kettle on the Missouri Coteau, southeast of Moose Jaw. A spruce woodland occupied this site from 10,3000-10,2000 yr BP, with deciduous parkland under moist condition until about 8800 yr BP, followed by dry climate with peak aridity by 7700 yr BP. Comparison with the timing of dry conditions in Alberta, as described above, demonstrates the progressively later onset of the hypsithermal from east to west. The termination of Yanza's record at 5.8 Ka BP represents the eventual desiccation of the slough. At Waldsea Lake, 100 km east of Saskatoon, hypersalinity and aspen parkland from

4500-4000 yr BP was inferred from the lithostratigraphy and pollen (Schweyen and Last, 1983; Last and Schweyen, 1985). The transition to cooler wetter climate occurred at 4000-2800 yr BP, with increasing abundance of pine and spruce pollen and mineralogy diagnostic of deeper water.

Recently there has been considerable interest in the paleohydrology and paleolimnology of the subhumid southern Interior Plains, mostly related to the Palliser Triangle Global Change Project (Lemmen et al*.*, 1993). To date, the source of the best record from the mixed-grass prairie is Chappice Lake, a small hypersaline lake in southeastern Alberta, about 75 km northwest of Harris Lake, the source of a long paleoclimatic record from the Cypress Hills, as described later in this report. A composite record spanning 7300 years of local environmental history was obtained from two cores (Vance, 1991; Vance et al., 1992, 1993; Vance and Mathewes, 1994; Vance and Last, 1994; Vance et al*.*, 1995). Carbonate-rich laminae, with abundant plant macrofossils indicative of hypersalinity, signal low water levels and periods of drought. Massive, silicate-rich beds, with fewer halophytic indicators, record higher lake levels, relatively fresh water and moister climate. During 6000-4000 yr BP, the presence of *Ruppia* pollen indicate high salinity, but not complete desiccation of the basin. There was declining salinity related to rising levels from 4400 to 2600 yr BP and a prolonged low-salinity, high water phase from 2600 to 1000 yr BP. In northwestern Montana, evidence of a cooler climate appears about 6000 yr BP, with progressively wetter conditions after 3600 yr BP (Barnosky, 1989).

Recent studies of peatlands in the southern boreal forest have provided further verification of the onset of cooler, moister climate after 6000 yr BP (Zoltai and Vitt, 1990; Kuhry et al*.*, 1992). Fluctuating water tables in the southern prairies prevent the development of peat bogs and fens. Thus peat accumulation is a proxy of persistently wet conditions. The development of peat was inhibited in the southern boreal forest by the warm dry conditions of the hypsithermal. From the distribution of modern and 6,000 yr BP peatlands, Zoltai and Vitt (1990) estimated that the 6,000 yr BP climate was 17-29 percent more arid than present, with growing degree days 6-20 percent higher and precipitation reduced by 19 percent.

TERRESTRIAL STRATIGRAPHY AND SOILS

The geologic and pedologic record of postglacial climatic change includes terrestrial Holocene stratigraphy, neoglacial chronologies, morphostratigraphic records (landforms), and paleosols. In the Interior Plains, rates of surface processes are climatically controlled (Wolfe et al., 1995; Campbell, 1997), since the region is tectonically stable, except for the slow rebound of the crust to the load of the continental ice sheet. Thus climate can be inferred from the characteristics of landforms, deposits and soils. However the influence of climate on weathering, erosion and soil formation is indirect, involving vegetation and the variable resistance of earth materials. Therefore inference of climatic forcing of geologic and pedologic processes from landforms and deposits involves much interpretation and a proper understanding of the role of climate in geophysical systems, or as Ritter (1988: 168-169) noted, with respect to geomorphology and climate:

> “Although geologists have always utilized tectonism or climatic change to explain changes in sedimentary sequences, or to reconstruct paleogeography, too many nagging questions remain about how the geomorphic screens function in response to climatic change or tectonism for us to assume that these interpretive leaps are easy or correct. The truth is that sudden changes in a sedimentary sequence cannot be confidently attributed to a specific geologic cause until we know more about the intermediate phase of geomorphic response. In fact, abrupt change in the depositional sequence is reflecting thresholds, complex response and episodic behavior within geomorphic systems, and we are only beginning to understand how those phenomena are reflected in sedimentary sequence.”

The inference of climatic forcing of geomorphic activity from sediments and sedimentary structures involves two dominant methodologies in the earth sciences: process studies and sedimentary geology. “The very nature of landscapes requires geomorphology to assume the dual nature of being both a historical and physical science" (Ritter, 1988: 160). Process geomorphology is very much based on the explanation of landform and sediment yield in terms of process mechanics, on the concept of the geomorphic system, and the time-independence of geomorphic activity. This is is a function of controls and resistance, rather than stage of landscape evolution over geologic time. Stratigraphic studies are naturally historical with the emphasis on chronology (time-dependence) and the age-correlation of lithofacies. Thus the understanding of climatic control of geomorphic process is from one tradition, while most of the evidence of landscape evolution is from another.

For several decades, the dominance of process studies in geomorphology has shifted the focus away from the study of landscape evolution over geologic time; process rates measured over several years or at most decades, do not account for the evolution of landscapes (Campbell, 1982; Eybergen and Imenson, 1989). Field experiments, however, have much improved our understanding of the climatic controls on geomorphic processes. Now environmental concerns, including global climate change, require the study of larger areas and time spans to establish environmental variability and the impact of human activities (Vitek and Giardino, 1993). A crucial source of long records is the landforms, soils and deposits inherited from past climates and climate changes.

Stratigraphic studies are typically based on the description and analysis of fragmentary deposits. The universal practice of categorizing strata is "almost a way of life" and "such arbitrary methods tend to perpetuate an illusion of security and precision in an apparently repeated confirmation of the original model" (Bowen, 1978: 7-8). Correlating glacial landforms, deposits and climate is an obvious case, and perhaps most easily justified since, on geologic timescales, glaciations are discrete and catastrophic. However the legacy of glaciers is out of phase with glacial climate. Most sediments and landforms were created during deglaciation as the ice sheet wasted and retreated in response to a warmer (i.e. non-glacial) climate. Also glaciers have a prolonged influence on the apparent response to postglacial climates, via the distribution of glacial drift, glacial tectonism, and re-configuration of drainage networks (Church and Ryder, 1972; Matheson and Thomson, 1973; Sauer, 1978; Christiansen and Sauer, 1988; Church and Slaymaker, 1989). The model of four Pleistocene glaciations lingers, even though, for example, between one and five glaciations can be inferred from the Quaternary stratigraphy of the southern Interior Plains (Ford et al., 1984). Where surface expression is lacking (*i.e.* older buried deposits), reconstruction of Pleistocene geomorphology is problematic, and thus an emphasis on age correlation and glacial chronologies may be more believed than real (Davies, 1989).

Transferring this methodology to postglacial environments and landscapes risks associating stratigraphic units with intervals of characteristic climate (*e.g.* Little Ice Age, hypsithermal) interpreted from other proxy data, mostly biological. Much of the present variation in sediment yield among climatic zones is explained by geologic controls, relief primarily and nature of the surface materials (Young, 1969; Clayton, 1983). For each climate zone, there is a zonal soil, representing the regional dominance of pedogenesis over geomorphic activity. Substituting space for time (*i.e.* using modern analogues of paleolandscapes) suggests therefore that paleosols are the geologic record of "stable" paleoclimates, and lithostratigraphy is a record of the periodic disequilibrium of geomorphic systems, in response to climatic change, extreme hydroclimatic events, internal perturbation of geomorphic systems, and/or lowered resistance of earth materials. The age-correlation of climate, sediment and landform implies time-equivalence, but deposits and landforms from one disturbance of a geomorphic system can have various ages as the impact of a storm or climatic change propagates through the system. The significance of this difference in age is relative to the recency of the event, but it does indicate the need to read stratigraphy in the context of the climatic control of geomorphic processes.

The non-linearity of geomorphic and hydrologic systems ensures that the pattern, rate and extent of landscape change is not related to climate in a simple fashion, and thus usually only a crude reconstruction of geomorphic process is possible from the analysis of landforms and sediments. This complexity in time and space is described by a body of concepts that are the foundation of a theory of geomorphic response to climatic change and variability (Brunsden and Thornes, 1979; Eybergen and Imenson, 1989; Brunsden, 1990, Schumm, 1977, 1981; Bull, 1991). Climate is the boundary condition, so that, while individual hydroclimatic events produce most geomorphic activity, their effectiveness depends largely on the climatic control of vegetation, weathering, and surface and sub-surface hydrology. Field experiments repeatedly show that meteorological data are a poor predictor of geomorphic response. High magnitude - low frequency (catastrophic) events tend to be over-represented, stratigraphically and morphologically. Their outcomes are persistent, unlike the typically more subtle imprints of quasi-continuous weathering, erosion and sediment transport, even with a maximum product of magnitude and frequency.

The deposits and landforms characteristic of one climate may be stable or unstable in an ensuing climatic interval depending on the nature of the climatic change. Where resistance is lacking, deposits are reworked and landforms modified, and the stratigraphic record can be biased in favour of the more recent events (Clayton, 1983). Most landscapes include elements that resist change, by virtue of geological properties and/or previous evolution to a stable form (Brunsden, 1993). In the Alberta badlands, for example, the mid-Holocene accumulation of loess (wind blown silt) initiated a period of reduced erosion, because it introduced higher infiltration rates than on the underlying Cretaceous shales (Bryan et al., 1987). Resistance can also result from disorder in hydrologic and geomorphic systems, as found in the young glacial landscapes of the southern Interior Plains.

Resistance accounts for most of the spatial variation in geomorphic response to climate, since earth materials are discontinuous, while the atmosphere (and thus climate-generated stress) is continuous (Sauchyn, 1997). Differential geomorphic activity commonly reflects the distribution of resistance and available sediment, or the unique histories of geomorphic systems, rather than spatial variation in the efficacy of climate as a geomorphic agent. In terms of timing and sequence, adjacent watersheds can respond to climate at different rates, and even at different times. This complex response (Schumm and Parker, 1973) includes feedback among processes, with the interaction of slopes and streams, for example, causing changes in rates of erosion and sedimentation that are largely independent of climate. Unusually thick sequences of sediment stratigraphy, which attract the Quaternary geologist, can represent a local lack of resistance or an atypical depositional environment (*e.g.* buried valleys), rather than a major climatic event or change.

With the high priority given to global change research, climatic change and variability have become a focus of the study of landforms and geomorphic processes (*e.g.* Thomas and Allison, 1993; Jones, 1993). Much of this literature is not explicit as to whether the landscapes are responding to climatic changes or a new equilibrium climate. The recognition of characteristic climates and corresponding processes and landforms, (*i.e.* climatic geomorphology) is not transferable as a methodology to landscape evolution. Erosion, mass wasting and sedimentation mostly reflects climatic instability, that is, response to new boundary conditions. Sediments and landforms are created by inevitable adjustments of geomorphic systems that are triggered by climatic change or extreme hydroclimatic events. Stratigraphy and landforms thus record both direct responses to climate and the indirect role of climate in geomorphic history. Isolating these different causes, and recognizing the climatic forcing of disequilibrium in geomorphic systems, requires a convergence of methodologies that have historically segregated the earth sciences (Ritter, 1988; Baker and Twidale, 1991). It also requires that earth scientists resist the tendency to uncritically perpetuate geochronologies, “the geo-historical tapestry which we have woven for ourselves and in which past students of landforms have been so intimately cocooned” (Davies, 1989: 7).

Proxy records

In Canadian prairies, recent research (Christiansen, 1979; Clayton and Moran, 1982; Klassen and Vreeken, 1987) favours extensive late Wisconsinan glaciation and thus postglacial landscape evolution of less than 15,000 years, and 12,000 or less over much of the region. Ablation of the Laurentide ice sheet would have been immediately succeeded by a period of paraglacial geomorphic activity (Church and Ryder, 1972). The stratigraphy of eolian, alluvial and lacustrine sediments overlying late Wisconsin drift suggest that much of the postglacial geomorphic activity had occurred prior to 3500 yr BP. Extensive deposits of sand dunes and loess (Catto, 1983; David, 1993; Vreeken, 1993) and much of the fill in depressions and channels have a late-Pleistocene origin (Klassen, 1994; Christiansen and Sauer, 1988). The most strongly developed paleosols in southern Alberta are from the early Holocene (Valentine et al., 1987, p. 228). Similarly, Turchenek et al. (1974) recognized two postglacial paleosols in central Saskatchewan. They are both overlain by eolian deposits, suggesting a return to drier condition at about 8,000 yr BP and 7,000 yr BP. Watters and Rutter (1984, p. 203) concluded that these early-Holocene soils had formed during a short period of landscape stability, "ending by the time of Mazama ash deposition" (6800 yr BP; Bacon, 1983). Despite the widespread presence of Mazama ash in the southwestern Interior Plains, chronological control is insufficient to correlate individual sedimentary units and paleoclimates or climatic changes. Incomplete surface cover and episodic, accelerated erosion would have characterized the hypsithermal landscape of about 7500-5000 yr BP. Few dated sections of mid-Holocene stratigraphy are described in the literature. Alluvium in Battle Creek valley, western Cypress Hills, (Westgate, 1972) and loess in southern Alberta and southwestern Saskatchewan (Vreeken, 1986; Bryan et al., 1987) suggest a period of increased erosion and sedimentation in response to reduced vegetation cover. Soil would have formed on desiccated lake beds, unless the sediments were susceptible to wind erosion. At Ear Lake, Saskatchewan, four successive lacustrine terraces formed with the drop in water levels (Mermut and Acton, 1984). The subsequent inundation of the lowest tow terraces, and accumulation of beach deposits over paleosols, began prior to 2000 years BP.

The period 5000-3000 yr BP is regarded as a time of landscape stability and soil formation on the southern Interior Plains (Valentine et al., 1987, p. 228). The transition to a cooler, moister climate is reflected in the apparent inactivity of floodplains and alluvial fans and the dominance of pedogenesis over fluvial and eolian erosion (Jungerius 1969; Jungerius and Mucher, 1969; Westgate, 1972). However, there may have been a greater incidence of mass wasting in the uplands and on large valley sides in response to groundwater recharge (Campbell and Evans, 1990; Sauchyn, 1990; Sauchyn and Lemmen, 1996). The global neoglaciation during 3000-2500 yr BP (Denton and Karlen, 1973) has been documented in the Canadian Rocky Mountains (Luckman et al., 1993). Leonard (1986) found increased glacial lake sedimentation in the same region after 4000 yr BP, reaching approximately present levels by 2750-2650 yr BP, and decreasing after about 2200 yr BP. Wilson (1987) showed that 3000-2500 yr BP was a period of downcutting in the Saskatchewan River system of western Canada, reflecting a cooler, moister climate. Similarly, Bryan et al. (1987: 145) speculated that incision of the Red Deer River “may have continued until the Little Ice Age, around AD 1500, coinciding with glacial advances in the Cordillera”. Downcutting by the mainstem streams would have triggered tributary channel erosion as their base levels were lowered. In this way, the impacts of climatic changes were propagated up the drainage networks.

TREE RINGS

Most instrumental records in western Canada provide a relatively short perspective, usually less than 100 years, on climatic variability. Therefore they are an inadequate basis for forecasting the severity and duration of future climatic extremes. A much longer perspective on the magnitudes and frequencies of extreme climate, such as drought, is available from proxy paleoclimatic data. Some of the best proxy data are indicators of lake level change and tree growth variation. Lake basin forests provide evidence of both. For example, Stine (1994) determined the radiocarbon ages of relict tree stumps rooted in present day lakes, marshes and streams of California's Sierra Nevada. The ages of these stumps and their present locations beneath surface water suggests "extremely severe drought conditions for more than two centuries before AD 1112 and for more than 140 years before AD 1350".

In seasonal climates, trees preserve a continuous record of annual climate. Dendrochronology is the study of growth rings in trees (Schweingruber, 1988). Dendroclimatology, the study of tree rings in relation to climate, (Fritts, 1976) is the only method of paleoenvironmental reconstruction that consistently provides annual resolution. The fundamental technique in dendrochronology is cross-dating, whereby distinctive series of narrow and wider tree rings, representing dry and wetter years, are identified and matched among trees of different ages. Calendar years can then be assigned to rings from dead wood. This extends tree-ring chronologies much beyond the life spans of living trees, and allows the dendrochronologist to determine the timing of pre-historic events that affected tree growth (e.g. droughts).

The search for proxy climatic data was the original application of tree rings. A.E. Douglass, the 'father' of dendrochronology was interested in the affect of sunspots on the earth's climate. In 1901, he noticed ring-width variations on a cut log and reasoned that these were controlled by the tree's environment (Fritts, 1976). Douglass (1920) illustrated the relationship between climate and ring width by plotting both against time, and introduced the technique of cross-dating by correlating ring-width signatures (sequences of wide and narrow rings) among trees distributed over large areas.

The reconstruction of pre-settlement climate is based primarily on the statistical relationship between ring width and meteorological data from the post-settlement period. Other tree ring parameters include wood density, the concentration of stable isotopes (Gray and Thompson, 1977, 1979), and widths of the latewood and earlywood in each annual ring. Over much of the Interior Plains, including the southern boreal forest (Larsen and MacDonald, 1995), tree growth is limited by the availability of water. Thus a record of precipitation variability can be derived from climatically-sensitive trees, those growing in well drained substrates where a continuous supply of water generally is not available (Stockton and Meko, 1975; Meko, 1992). At altitudinal treeline in the Rocky Mountains and northern treeline in Manitoba, tree rings are a record of growing season temperature and/or length. The characteristics of tree rings also have been correlated with hydrologic parameters, such as stream flow and lake levels (Stockton and Fritts, 1973).

Proxy records

In western Canada, dendrochronology has been largely confined to the montane and boreal forests (Case and MacDonald, 1995; Luckman and Innes, 1991). An investigation of fire and insect infestation frequency in the jack pine forests of Manitoba (Gill, 1930) was the first Canadian study to use ring-width data and cross-dating techniques to develop a tree-ring chronology. Shortly afterwards, Powell (1932) compared variation in wheat yields in Saskatchewan to ring-width variation in white spruce and some hardwood species. Much of the tree ring research in western Canada has been based at the Laboratory of Tree Ring research in Tucson, Arizona, including the first studies of Douglas Fir in Alberta (Schulman, 1947), the first regional dendrochronological network for western North America (Drew, 1975), regional climatic reconstructions (Fritts, 1971; Fritts et al*.*, 1979; Fritts and Lough, 1985), and a dendrohydrological study of the Peace-Athabasca delta (Stockton and Fritts, 1973). One major exception is the research group at the University of Western Ontario which has established long tree-ring chronologies for the Canadian Rockies, to reconstruct climatic and glacial history of the last millennium and evaluate tree growth - climate relationships at altitudinal treeline (*e.g.* Luckman, 1995, 1996; Luckman and Colenutt, 1992). Long chronologies have been constructed for *Pinus albicaulis* (white bark pine) near Bennington Glacier, *Picea engelmannii* (Engelmann spruce) and *Pinus albicaulis* near Peyto Glacier and *Larix lyalli* (alpine larch) at Gray Pass. The earliest dates in these chronologies range from 760 to 1104 AD. Dates of tree mortality and growth suppression correlate with periods of moraine development in the 18th and 19th centuries. Thus these high-resolution tree-ring data record the Little Ice Age in the Canadian Rockies. They also provide an annual record of temperatures for an entire millennium.

Case and MacDonald (1995) constructed a 487-year record of annual precipitation from *Pinus flexilis* (limber pine) in the foothills of southwestern Alberta. They determined a drought return period of 30-50 years, which has not changed appreciably over the past five centuries. Severe drought in the 1790's in their record, was previously identified by Sauchyn and Porter (1992) from the Cypress Hills. In Manitoba, Nielsen (Manitoba Geological Survey, personal communication, March, 1997) has established a oak chronology back to 1660 and collected oak from the deposits of the Assiniboine and Red Rivers that dates to > 2000 years BP. Although a belt of aspen parkland extends across the prairie provinces, much of the original aspen poplar (*Populus tremuloides*) was removed for crop production and this tree species is much inferior to coniferous trees for dendroclimatic research (Fritts, 1976). The growth rings are indistinct and do not necessarily correspond to calendar years.

Tree ring chronologies are lacking for the region where climatic variability most heavily impacts human activities, that is, the subhumid plains, the only major region of Canada lacking surface and soil water, and therefore trees. However trees are not completely absent. The western Cypress Hills, near the geographic centre of the Palliser Triangle, support an extensive coniferous forest, providing a unique opportunity for tree-ring research in an otherwise grassland landscape (Sauchyn and Porter, 1992). The dendroclimatology of this area is discussed below in the section on the proxy records from the western Cypress Hills.

Another dendroclimatic study from within the prairie ecozone was a preliminary investigation of tree stumps exposed along the shores of White Bear (Carlyle) Lake in southeastern Saskatchewan (Sauchyn, 1995). The radiocarbon age of two *Populus tremuloides* (aspen poplar) stumps were 100 +/- 150 yr BP and modern. These results indicate that the relict tree stumps are remnants of a forest which occupied the lake basin within the past 200 years. Although these imprecise age estimates do not reveal the exact timing of flooding and mortality of the trees, these events were relatively recent and thus can be corroborated from historical records. Local residents reported that lake levels were very low when the region was first settled by EuroCanadians in the latter part of the last century. Apparently the lake was separated into three basins and land currently under water was a hay meadow. Similarly the analysis of aspen stumps from Basin Lake north of Saskatoon also yielded a modern radiocarbon age and local accounts of "trees having been drowned during the late to middle decades of the past century" (S. Stine, California State University, personal communication).

HISTORICAL DATA

The EuroCanadian (non-aboriginal) history of the prairie provinces is several centuries longer than the instrumental climatic record, which began with the agricultural settlement of the southern prairies. Whereas tree rings are a source of annual proxy data for the historical period, more direct records of weather and climate and related events (e.g. floods, ice cover) are available in archival documents, particularly, the reports of explorers (e.g. Palliser, 1859) and staff of the fur trading companies. Use of historical data for the reconstruction of climate on the prairies has been essentially limited to Manitoba, where colonies in the Red River valley predate settlement elsewhere on the prairies by about 50 years. Also, probably the best source of phenological data is the Hudson Bay archives in Winnipeg. The climatic parameters which are most apparent in these archives relate to ice conditions on the rivers and lakes. The first EuroCanadians were dependent on the lakes and streams for transportation. Also ice formation and breakup marked the beginning and end of the harsh winter season and thus were prominent in the minds of these people. Dates of annual ice breakup and freezeup have been studied for the Red, Churchill, Hayes, Albany, and Moose Rivers (MacKay and Mackay, 1965; Catchpole et al*.,* 1976; Rannie, 1983) and for Hudson's Bay (Catchpole, 1978, 1985). More recently, Blair and Rannie (1994) documented the unusually cold and wet weather of the spring and summer of 1849. These studies offer the most detailed reconstructions of pre-instrumental climate, identifying the extremes of annual and seasonal climate that have occurred over the past several centuries. They also are valuable verification for the results of tree ring analysis.

Even since the settlement of the prairie provinces, instrumental climate data have been lacking for the higher latitudes and altitudes. In the Rocky Mountains, glacier mass balance is good proxy of annual climate. It has been related to climate variability at several scales. For Canada, however, the longest "true" glacier mass balance time series are shorter than the response time of the glaciers to climate forcing. This limits the reconstruction and forecasting of climate, using a mass balance-terminus response model and terminus fluctuation data, for which extensive proxy records exist for numerous glaciers in the western Cordillera since about 1850. Various researchers have related glacier mass balance variations to meso-scale climate as measured by standard meteorological observations. Other work has examined synoptic-scale climate influences. Recent work at Peyto Glacier in the Rocky Mountains, also on synoptic scale influences, considers the influence of winter climatology and atmospheric circulation on the evolution of the mass balance time series (M. Demuth, NHRI, personal communication, March 17, 1997).

There is an interesting coherence of mass balance time series in the Cordillera. While individual magnitude variations are often less than the regional noise when examining the global glacier mass balance data set, the variations for individual glaciers are clearly in-phase and their magnitudes commensurate with meso-scale climatic regimes. Glacier mass balances are a key indicator of changes in the surface heat flux. Mass balance response to "warming" will vary depending on the climate regime. For example, high latitude, maritime glaciers will likely exhibit positive mass balances because of increased precipitation in the form of snow in winter. Glaciers in dry continental climates, like the Rocky Mountains, will likely exhibit negative mass balances because of a general reduction in moisture. The former sites will respond in the long-term by increasing their areal coverage (advancing); the later will shrink.

PROXY RECORDS FROM THE WESTERN CYPRESS HILLS

The West Block of the Cypress Hills, in southwestern Saskatchewan and southeastern Alberta, rises to 1465 m, the highest elevation in the Interior Plains. Therefore the vegetation is a mosaic of grassland, aspen forest, coniferous forests, and wetlands. Given the comparatively large relief and complex topography, and ecotonal vegetation, the ecosystems and geomorphic systems of the Cypress Hills are more sensitive to climatic change than natural systems in the surrounding landscapes of lower relief and plant diversity. Consequently this landscape can be expected to yield a detailed chronology of Holocene paleoenvironments (Sauchyn, 1993). The permanent lakes and coniferous forest are important sources of proxy paleoclimatic data. Following is an overview of paleoenvironmental research in the western Cypress Hills.

Paleolimnology and paleoecology

One of longest and most complete records of lake sedimentation from the Canadian plains is based on two cores from Harris Lake, Saskatchewan. Sauchyn (1990) and Sauchyn and Sauchyn (1991) established the chronostratigraphy of a 9.6 m (9120 years) core and interpreted Holocene paleoclimate from the organic matter and pollen contents. A 10.4 m core (9249 years) was the basis for three subsequent investigations. Last and Sauchyn (1993) reconstructed paleohydrology from the mineralogy and lithostratigraphy, Wilson et al. (1996) inferred paleosalinity from the diatoms, and Porter and Sauchyn (submitted) interpreted Holocene paleoenvironments of the Harris Lake watershed from the ostracode taxa. There is good chronological control on these records, with AMS dates, and Mazama tephra.

The 9120-year pollen profile from Harris Lake is one of the few continuous pollen records from the northern Great Plains which extends to the early Holocene. It indicates that a *Populus tremuloides* (aspen poplar) forest-grassland complex was established by 9000 yr BP; very little coniferous forest was present at that time. Extrapolation from other sites suggests that this vegetation is probably not a remnant of early post-glacial treeless vegetation, but rather developed in response to the beginning of more arid conditions documented elsewhere (Vance, 1986; Ritchie, 1987; MacDonald, 1989). The predominance of grassland and saline-tolerant vegetation between 7700 and 5000 yr BP defines the hypsithermal for this region. This agrees with other dates for the hypsithermal from the northern Great Plains (Ritchie and Lichti-Federovich, 1968; Lichti-Federovich, 1970; Schweger et al., 1981; Vance, 1986; Barnosky et al., 1987; Barnosky, 1989; MacDonald, 1989; MacDonald and Reid, 1989). Moreover, maximum aridity appears to have occurred around 7700 to 6800 yr BP, as indicated by the dominance of grassland taxa, low levels of conifers and *Betula*, intermediate levels of *Populus*, minimum percentages of Araceae, *Myriophyllum*, *Triglochin*, and *Sphagnum*, and relatively high levels of Cheno/Am. Again this agrees well with other evidence for maximum aridity on the northern Great Plains (Barnosky et al., 1987). The gradual decline in Cheno/Am pollen and minimal aquatic pollen, including *Typha*, further indicate that lake levels were extremely low with minimal fluctuation and that the warm, dry period was fairly climatically uniform.

Climatic deterioration followed, as indicated by increases in relative amounts of conifer and aquatic taxa pollen. The *Pinus contorta* and *Picea glauca* forests, characteristic of the Cypress Hills today, only have been prevalent since about 4600 yr BP; both species were present in very low numbers throughout the hypsithermal. By 3230 yr BP the modern vegetation was established, with little change since then. The development of a cooling trend around 5000 yr BP, agrees well with the timing of climatic deterioration established by palynologists working in surrounding areas: 5500 yr BP at Toboggan Lake in southwestern Alberta (MacDonald, 1989); no later then 4000 yr BP at Waldsea, Saskatchewan (Last and Schweyen, 1985); about 4500 yr BP in central Alberta (Vance, 1986); and between 4000 and 3000 yr BP at Lofty Lake, Alberta (Lichti-Federovich, 1970; MacDonald and Reid, 1989). Farther west, Barnosky (1989) determined that the cooling trend at Lost Lake, Montana, began about 6000 yr BP and that after 3600 yr BP the climate became progressively wetter. In southern Manitoba and the US Midwest, climatic deterioration began about 3000-3500 yr BP (Ritchie and Lichti-Federovich, 1968; Winkler et al., 1986; Ritchie, 1987). Thus the onset of cooling in the Cypress Hills is intermediate between earlier times to the west and later times to the east, supporting the hypothesis (Barnosky et al., 1987; Anderson et al., 1989) of delayed climatic change in progressively eastern sectors of the northern Great Plains.

The modern Cypress Hills vegetation developed around 3200 yr BP. Again this agrees well with dates for the establishment of modern vegetation in nearby areas (Ritchie and Lichti-Federovich, 1968; Ritchie, 1969; Lichti-Federovich, 1970). Other studies, however, have found little vegetation change since about 5000 yr BP in Alberta (MacDonald, 1989) and even earlier in south-central Saskatchewan (Mott, 1973). The most evident late-Holocene changes in the Harris Lake record are the decline in *Betula* and increase in *Pinus*. As cooler and wetter conditions developed, *Picea* and especially *Pinus* spread, presumably from small isolated stands which survived the hypsithermal, to become major vegetation types in the West Block. The prominence of coniferous forest in the modern vegetation mosaic is, therefore, a recent phenomenon.

The availability of ostracode, diatom and mineralogical records for Harris Lake gives greater validity to the reconstruction of paleoenvironments. However, discrepancies are bound to occur by virtue of differences among the proxies in terms of sampling intervals and the signals preserved in the various constituents of the lake sediment. The subjectivity of delimiting paleoenvironments would also account for some discrepancy. The diatoms and ostracodes are sensitive to more local conditions than the pollen, although small shallow basins, such as Harris Lake, tend to preserve a more local signal of vegetation change. The influence of the immediate environment on ostracodes is most evident in the reconstruction of vegetation. The ostracode assemblages from 3600 BP to present are typical of forested environments, yet grassland occupies the north shore of Harris Lake and is present in the pollen record (Sauchyn and Sauchyn, 1991). The ostracode habitat is strongly influenced by the forest that dominates the watershed.

The early pollen and ostracode data agree on dominance of grassland in an aspen-parkland complex. A substantial increase in *Pinus* pollen after 4500 BP coincides with an ostracode assemblage characteristic of subboreal mixed forest. However a major change in the ostracode record, indicating increased temperature and precipitation during 7700-6400 BP, contradicts the pollen interpretation of this period as most arid. Timing of the hypsithermal is 7700-5000 BP in the pollen record versus 6400-4500 BP from the ostracodes. Whereas the mineralogy revealed short episodes of hypersalinity in the early to mid-Holocene (Last and Sauchyn, 1993), there is no evidence of significant changes in lake depth and salinity (chloride concentration) in the ostracode record. Similarly the diatom record indicates persistent freshwater conditions (salinity < 0.5 g L^{-1}) throughout the Holocene (Wilson et al., 1996). However it also suggests that, between 6500 and 5200 BP, paleosalinity was highest and lake levels were relatively high. This contrasts with the ostracode reconstruction of reduced salinity and relatively low lake level during this interval. Whereas variation in these various proxies mostly is a function of climatic forcing, there is also evidence of change produced by geological events. Landsliding west of the lake (Sauchyn and Lemmen, 1996) is the best explanation of a distinct change in the rate and type (siliclastic to endogenic) lake sedimentation, that is apparent in both the lithostratigraphy and ostracode record.

A complete synthesis of the proxy records from Harris Lake will require further analysis and interpretation in the context of a unique limnological setting: a shallow lake but never dry, groundwater dominated, coniferous forest, variable and relatively high rates of geomorphic activity and lake sedimentation. These characteristics distinguish Harris Lake from other lakes in subhumid environments, which serve as the modern analogues for our interpretation of Holocene paleoenvironments.

Soils and lithostratigraphy

The lithostratigraphy of Harris Lake can be combined with information on terrestrial deposits to create a geological interpretation of postglacial climatic change in the western Cypress Hills. Landscape stability in the cool climate of the early Holocene is indicated by strongly-developed paleosols in southern Alberta (Valentine et al., 1991; Waters and Rutter 1984), and low sedimentation rates in Harris Lake (Sauchyn, 1990). These proxies pre-date the deposition of

Mazama ash at 6800 yr BP (Bacon, 1983). Various stratigraphic data then signal warmer, drier climate, reduced vegetation cover, and disequilibrium in the fluvial and eolian geomorphic systems. In Harris Lake, from 6100-5300 BP, the rate of sedimentation was considerably higher and organic matter declined to less then 7 percent, indicating lower plant productivity and higher yields of mineral sediment. (Sauchyn, 1990). Post- Mazama loess (Vreeken, 1986), and alluvial sedimentation during 7300-3880 yr BP in Battle Creek valley (Westgate, 1972), are further stratigraphic evidence of accelerated mid-Holocene geomorphic activity in response to a dry climate.

A transition in dominant Holocene geomorphic processes, from fluvial and eolian erosion before 5100 yr BP to landsliding after 4500 yr BP, corresponds to a significant mid-Holocene climatic change from the dry conditions and phytoinstability of the hypsithermal, 7700-5100 yr BP, to maximum humidity during the period 4500-3000 yr BP. Sparse pedologic and stratigraphic evidence from the Cypress Hills suggests that floodplains and alluvial fans were relatively stable (Jungerius 1969; Jungerius and Mucher 1969; Westgate 1972). However the sedimentation rate from 5120-3450 yr BP is the highest for the Harris Lake core, demonstrating the significance of landslides as a source of mineral sediment (Goulden and Sauchyn, 1986). From the radiocarbon ages and polygenetic profiles of buried soils, Jungerius (1969) and Jungerius and Mucher (1969) concluded that 4500-3600 yr BP was a time of major forest expansion and maximum Holocene humidity. Lower temperature and plant productivity are implied by the relatively low percentage of organic matter in the Harris Lake sediments from 3000-2400 yr BP. This cool period coincided with a global phase of glacier expansion (Denton and Karlen, 1973), including a 'mid neoglacial' advance in the Canadian Rocky Mountains at approximately 3000-2500 yr BP (Luckman et al., 1993).

Tree rings

Tree rings from the western Cypress Hills offer a high resolution proxy, although only for the past several centuries. Porter (1990) contructed a white spruce chronology that extended only from 1843, because 145 years was the age of the oldest tree sampled. However, significant correlations between ring widths and climatic parameters suggested that further dendroclimatic research in the Cypress Hills could generate valuable information on the pre-settlement variability of precipitation in southwestern Saskatchewan and southeastern Alberta. Older dead wood was therefore collected to extend the tree ring chronology back to 1778 and reconstruct summer precipitation (Sauchyn and Porter, 1992). Despite its relatively short length, this tree-ring chronology is the only one from the interior of the subhumid plains. The length of the chronology is constrained by the age of the living trees, less than 200 years, reflecting their relatively short life spans, frequent pre-settlement fire and post-settlement demand for wood in an otherwise treeless landscape. Therefore subsequent research has focused on the collection of wood from log buildings constructed by the NWMP and the first EuroCanadian traders and settlers. They used trees that pre-date the fires of the 1880's that almost completely destroyed the forest of the Cypress Hills. The age of this wood can be known from cross-dating and written and oral history. These additional ring-widths from old wood has recently extended the tree ring chronology to about 300 years.

Reconstruction of the pre-settlement precipitation in this region was based on the statistical relationship between standardized ring widths and instrumental meteorological data. Different sets of climatic data were used for the modeling and verification of reconstructed climatic parameters. The calibration of a regression model was based on ring-width indices for the period 1974-90 and climate data, for the same period, collected by the Alberta Forest Service at the fire tower near Elkwater, Alberta. The highest correlation among climatic variables and ring-width was between combined June-July precipitation and the ring-width residuals (*i.e.* width corrected for the effect of age). None of the correlations involving temperature variables were significant, as expected, since the climate is subhumid and trees were selected from the driest sites. Other correlations were based on the assumption of a lag between precipitation and tree growth (*e.g*. 14-month precipitation (Fritts, 1974), from June of the previous year to July of the current year). These variables were not significantly correlated with ring width, due possibly to the nature of the substrate. The Cypress Hills formation consists mostly of porous sand and gravel, inhibiting retention of moisture from one year (or one month) to the next. Thus tree growth in the Cypress Hills, near the geographic centre of the driest of the Palliser Triangle, is limited by summer precipitation. July has the highest temperatures and greatest number of sunshine hours (Cowell, 1982), resulting in highest evapotranspiration and moisture stress. June precipitation has the greater influence, because tree growth begins to slow in July. Over much of the Interior Plains, including the southern boreal forest (Larsen and MacDonald, 1995), tree growth is limited by the availability of water.

The annual variation in summer precipitation has strongly influenced the agricultural history of the Palliser Triangle and, in particular, settlement and subsequent depopulation (Jones, 1987). Above or near average precipitation during much of the 1910s prompted massive expansion of cereal crop production. Dry years in the latter part of the decade, and during the 1920s, were a precursor to the drought of the mid-1930s and its devastating effect on dryland agriculture. These and subsequent climatic anomalies (*i.e.* above average precipitation in the 1940s and 1970s; drought in the 1980s and early 1960s) are reflected in the tree-rings, but also well documented in the instrumental climatic records. Therefore the more useful information in the Cypress Hills dednroclimatic record is the pre-settlement precipitation variability. A drought in the 1790's was the most prolonged and extreme of the past two centuries. Drought in the early- and mid-19th century also was more severe than any experienced by prairie farmers. These droughts were followed by long periods of consistently above average precipitation that have no analogues in the present century, except perhaps the 1970s. Thus the major conclusion from this reconstruction of June-July precipitation for the years 1778-1990 is that the recent occupants of the Palliser triangle have not yet experienced the extremes of summer precipitation that occurred in the 19th and late-18th centuries and that could reoccur in the near future.

RESEARCH NEEDS AND RECOMMENDATIONS

Despite the more than 40 years of scientific activity, and some 400 studies, cited in this report and the companion bibliography, there remain significant gaps in our understanding of the postglacial paleoenvironments of the Canadian prairie provinces. This is a very large region with considerable diversity from the subhumid to semiarid Palliser Triangle to the subarctic to high mountain landscapes. Methods are constantly being developed and improved for the extraction and analysis of climate proxies. From this review of the existing paleoenvironmental database for the prairie provinces, the most obvious deficiencies are high resolution data and, geographically, the prairie ecozone. Despite the recent paleoclimatic research sponsored by the Palliser Triangle Global Change Project (Lemmen et al*.*, 1993; Vance and Last, 1995), there are still relatively few good records from the subhumid plains (Wilson et al., 1996; A. Beaudoin, Alberta Provincial Museum, personal communication, February 3, 1997; B. Vance, GCS, personal communication, January 31, 1997). Therefore the **first recommendation** of this report is that research on the postglacial paleoenvironments of the subhumid southern Interior Plains be encouraged, taking advantage of interest and expertise developed under the Palliser Project.

The reconstruction of environmental history (hindcasting), irrespective of the proxy, is based on the understanding of natural systems and their relationship to climate; “the present is the key to the past”. Thus our interpretations of proxy data are only as good as the database of contemporary ecological, hydrological, meteorological and geological data. Paleoecology requires an understanding of the autecology of the organisms that are preserved in sediments and the controls on species distribution and range. Paleolimnology requires various data on the physical and chemical characteristics of lakes, including the groundwater controls. The climatic forcing of geological processes can be reconstructed from deposits and landforms only with knowledge of the behavior of geomorphic systems. Therefore the **second recommendation** is support for the monitoring of ecological, hydrological, meteorological and geological processes. Unfortunately support for such baseline monitoring has been fading, as epitomized by cutbacks at Environment Canada, whereby first the sediment program, and more recently water quantity and quality monitoring, have been seriously curtailed. The lack of these data seriously constrains our ability to interpret proxy paleoenvironmental data.

The monitoring of processes reveals the immediate responses of natural systems to hydroclimatic events, but only for current climatic conditions. Long stratigraphic records, on the other hand, uncover the extremes and periodicity of environmental change, but the generally low resolution limits the inference of climatic controls. Thus intermediate spatial and temporal scales seem best suited for the reconstruction of paleoclimate with reasonable resolution, but also over sufficient time that both climatic variability and change are detectable. Proxy records from the past millennium offer the best opportunity to resolve climatic variability or at least the range of climatic extremes. Presently there seems to be a gap between the tree ring records of annual resolution, but short duration (centennial), and the lake sediment records of long (millennial) duration but generally low resolution (decadal to centennial). Therefore the **third recommendation** is that research be encouraged to extend the length of tree ring chronologies and the resolution of stratigraphic work such that overlap of the two databases can provide a high resolution record for the past millennium.

The key to any further high resolution paleolimnological research work in the prairie provinces will be the study of highly sensitive proxies, such as plant macrofossils, aquatic organisms and the isotopic composition of all natural archives (Gray and Thompson. 1977, 1979; Edwards et al., 1996) and of laminated sequences of "event stratigraphy". Nearly all of these laminations are chemically-generated and do not necessarily have any underlying temporal sequence. That is, they are not necessarily annual or seasonal, and probably differ between lakes and even within a given section of the same lake. Even so, laminated sequences are important because (i) they are a snapshot of an event in the history of the basin; these snapshots (laminae) can be put together to form a history, and (ii) methods have been developed recently to analyze the composition of individual laminations. New approaches to lacustrine mineralogy (W. Last, University of Manitoba, personal communication, March 6, 1997) include studies of the fluid-inclusions of endogenic precipitates. The various precipitates (salts, calcite, *etc.*) in prairie lakes are ideal for this work. Proxy data include temperature of formation, composition of water, and even the meteoric isotopic composition. Also, reconstruction of the thermodynamics of lake sediment precipitation supplies information about, not only the composition of the water, but other environmental conditions like relative humidity.

In terms of extending the tree ring record, several excellent opportunities exist for dendroclimatic research in the heart of the most poorly understood region, the subhumid plains. White spruce (*Picea glauca*) occupy upper north-facing slopes in the Red Deer river valley near Drumhellar and deeply-incised tributary coulees to the south and west (*i.e.* the valleys of the Rosebud River and Kneehills and Ghostpine creeks). Stands of spruce on steep north- and east-facing slopes are in sharp contrast to barren badlands on the opposite valley sides, cropland on the adjacent prairie and the deciduous trees on the crests of the Hand Hills and Wintering Hills. This unusual forest represents the limit of white spruce on the southern Canadian plains (Zoltai, 1975).

The West Butte of the Sweetgrass Hills on the international boundary, near Coutts, Alberta, rises about 1000 m above the surrounding plains and thus supports an extensive coniferous forest (Thompson and Kujit, 1976). These trees are potentially the source of a very long, high-resolution data base of proxy precipitation for the southwestern Canadian plains. The forest includes hybrid spruce (*Picea glauca X engelmannii*), Douglas fir (*Pseudotsuga menziezii*), whitebark pine (*Pinus albicaulis*), limber pine (*Pinus flexilis*), lodgepole pine (*Pinus contorta*) and subalpine fir (*Abies lasiocarpa*). Other dendroclimatic studies have demonstrated that these species have distinct ring width signatures that correlate among sites and with instrumental climatic data. Elsewhere they have been the basis for long paleoclimatic records (Luckman et al*.,* 1984; Swetnam and Brown, 1992). The diversity of this forest is in sharp contrast to the Cypress Hills, where the only conifers are white spruce and lodgepole pine, and the Drumheller area, where white spruce is the only conifer. The Douglas fir, whitebark pine and limber pine are particularly interesting, because they are much longer lived than other conifers. Thus some of these trees may be the source of more than 500 tree rings in a single sample.

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PROXY RECORDS OF POSTGLACIAL CLIMATE IN THE CANADIAN PRAIRIE PROVINCES: A GUIDE TO THE LITERATURE AND CURRENT RESEARCH

D.J. (Dave) Sauchyn, Professor
Department of Geography
University of Regina

May, 1997

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