Biological Implications of Global Change: Northern Perspectives

Edited by: Rick Riewe and Jill Oakes

Canadian Circumpolar Institute
Biological Implications of Global Change: Northern Perspectives.

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INTRODUCTION:
CLIMATE OF CHANGE

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An integral part of human nature is our curiosity, our desire to learn and to know. To develop an understanding of the world around us has been a basic desire since humans began to formulate their thoughts (Aristotle). The ability to manipulate natural forces which followed from the ever-increasing understanding of the laws of nature has proven to be of extraordinary benefit. We have learned how to expand our extracting capacity with respect to needed resources, and, as a result, the human population began to increase steadily. More recently, the increase has become explosive, resulting in population levels close to the Earth’s carrying capacity. This can hardly be sustained in perpetuity.

Yet it is only the smaller part of the human race which enjoys the current prosperity. The vast majority of humanity, together with most of the other cohabitants of this planet, derived little benefit and much hardship from technological civilization. Immeasurable numbers of individuals and species have perished in the process of human global expansion and its accompanying ills. Ecologically speaking, humans have proven to be the fiercest inter- and intraspecific competitor on Earth (Brown, 1990).

_Homo sapiens_ has become a factor of almost geological proportions. The geo-historical era, characterized by human dominance, has been called Anthropozoicum by some, and sardonically, the “Quintenary Period” by others (Sterba, 1993). According to this view the Quaternary era “ended” when the first synthetic products unknown to nature were released by humans into the air, water or ground. Similarly, the Biosphere, modified by humankind, has become the Anthroposphere or the Homosphere (Svoboda, 1989). Things will never again be the same.

Periods of mass extinction are a normal part of evolution, as evidenced by the fossil record; however, the biological shift is by definition a drastic one. The most recent and most publicized of these, the Cretaceous-Tertiary transition some 65 million years ago, ended the era of the dinosaurs and changed the face of the Earth forever. Since that time, the Biosphere and its Biota have not been subjected to a greater threat, fatal to so many organisms, as during the recent and short human era. Agriculture, communications and technology have helped to create the environment for mankind’s uncontrolled expansion; overgrazing, overhunting, deforestation, erosion, habitat destruction, global pollution, etc. have been the devastating results.

The cataclysmic impact of the meteorite which is believed to have ended the Cretaceous era and left its signature in the distinct Cretaceous-Tertiary (C-T) boundary is being replicated by the less sudden but potentially as pernicious impact of our own burgeoning civilization. We have already left a definitive geological marker comparable to the C-T boundary. New and often permanent layers of trash, radioactive and synthetic substances have been deposited everywhere on the Earth’s surface, in the deep oceans, and in outer space.

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² Doris Nabert is a graduate student at the Department of Botany, University of Toronto. She has been conducting her research in the Canadian High Arctic.
Rising concentrations of primarily industrial waste gases as well as those released through our influence on natural systems have brought about the phenomenon of "climate change", astonishing in its global implications. More recently this watchword has been broadened to the more encompassing "global change". The new term includes all the effects, factors and variables by which the structure and functioning of the present Homosphere diverges from the unaltered Biosphere of the past.

The idea of the "climate of change", as used in the title of this essay, puts additional emphasis on a major underlying cause of global change, the powerful intellectual climate of developing humanity seeking emancipation from the laws of nature. This "climate" has intrinsically generated never-ending modifications within human society, and some deliberate modifications in the environment of our planet as well. It could be described as the "incandescence" of the Noosphere, that is, the fiery activity of the sphere of human reasoning which has led to the ongoing transformation of the Biosphere into the Homosphere, with all its attendant consequences.

This same intellect must now be called upon to correct the unwanted side-effects of the ages-long tampering with natural systems. There can be no single or simple solution for this overwhelming task, for the destructive process is still unfolding. There are, however, some signs of promise. The public is now being informed about environmental "issues" on a daily basis, and in the realm of politics, many far-reaching initiatives are beginning to take shape. Additionally, the scientific search for these solutions, as reflected in the number of papers and conferences concerned with global change, is stepping up its pace. All this together suggests that the intellectual "corrective feedback" has been fired up and can work towards regaining first the truce and ultimately a new balance with nature. The following papers and abstracts were presented at the Biological Implications of Global Change: Northern Perspectives workshop held at the University of Alberta, October 22 and 23, 1992.

REFERENCES CITED
Aristotle. Metaphysics. Bk.1, Ch.1
ANGRY SPIRITS IN THE LANDSCAPE

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Environment is an Inuit affair, it has always been and still is to this day. No traditional hunter has ever moved from one hunting area to another without consulting the environment either by eye, feel or traditional knowledge passed on verbally from one generation to another. Environmental awareness in Inuit culture begins at a very early age. Different parents have different systems for teaching this awareness. It also depends on the child; some children learn very fast and others take their time. My brother and I were brought up by our grandparents. A lot of families consider that a luxury, being brought up by the grandparents. The explanation behind that belief is a totally different environment than the one I am going to be talking about.

I hear from grandmother to this day when I awake in the morning: “Go out and look at the world”. When I first moved to southern Canada I never worried about those upbringings, mainly because I was too young, and thinking about those beliefs had not yet sunk into my system. But what you hear as a child does sink in eventually. And oddly it becomes your conscience.

As I got older, living down here in the south I noticed my body craved greatly for the outdoors, for air, proper snow, streams, ice, the sound of landscape moved by breezes, gentle, medium and sometimes very harsh. I grew up with the environment being a very important part of my life. It had to do with everything for my survival. My father and grandfather and uncles could not go out hunting unless the weather was right for them. The right weather also depended on what kinds of animals were to be hunted. Some animals can only be hunted in some types of “bad” weather, for example on a windy day.

I think my brother and I grew up during the best solid years, before certain changes began to take place in the environment. At that time, the sun came back with the right kind of heat and gave us the right kind of spring season. The sun had the right heat, the snow began to melt at the right rate, at the right time, the right month. At least to us humans it was the right time. How do I know the whole environment had not evolved long before I was born, that James Bay and Hudson Bay were at one time like Florida? However, the weather conditions during spring time in James and Hudson Bays were always the right time. The little snow bunting began to arrive and began feeding on last year’s berries. The ptarmigan began to change the colours of their feather coats, like the arctic hare. By this time, the streams were running and the ice covering small lakes all melted. Suddenly you began to hear geese and ducks flying by, and the seals began sunbathing on the top of the ice. Before long, people could no longer go out anymore with the dog team, out on the sea ice. The big cracks on the ice had opened up. The summer has arrived in the Arctic.

It is about the beginning of June now. Nobody can move anymore. Everybody is waiting for the sea ice to leave. Even the big wind was reliable during that time. The hunters patiently waited for the big southwest wind. When it came, the big cracks on the ice would turn into big waves and the thin ice would crumble and, if the wind persisted, the ice would leave James Bay and move out into Hudson Bay and eventually it melted away. Open water means freedom for the hunters. They can take their boats now and hunt anything: seal, whale, walrus, polar bear.

1 Minnie Freeman was born in a small hunting camp on Cape Hope Island in James Bay. She is well known for her poems, short stories and her autobiography, Life Among the Qallunaat, which was published as a book and produced as a play.
The summer arrived in James and Hudson Bays. The weather is always steady with occasional rain and big thunder storms, otherwise very reliable for hunters to take their boats and canoes to another fiord or cove to hunt seals. The sun-dried meats would begin to hang out depending upon which woman was the most industrious and non-wasteful. When men are busy gathering food, women are busy gathering wood, sea urchins and mussels, while waiting for berries to ripen. Others are gathering sphagnum moss for babies’ and women’s diapers for the coming winter. Winter gear is being repaired or replaced depending upon what kind of successful hunt men had during the summer. At this time the children are being trained how to tell a grey or white beluga whale coming into James Bay. How to tell a white beluga from a white cap is quite a job for inexperienced little eyes. Our jobs very often ended up being part of our education on the conditions of the sea.

Looking back on those years, we the generation from that period were secure even though we were hearing our grandparents predicting the different conditions that will comprise our future environment. As children, at least my brother and I were hearing that large changes and unsettled weather conditions were coming. That a lot of angry spirits in the landscape would cause hot fires to erupt. That some parts of the earth would crumble. That violent storms would suddenly erupt in any corner of the world. To me, as a child those predictions were just stories. “When is this happening?” my grandmother would ask. “Maybe not now, maybe in Mini and Miki’s time or after”. Believe me, it was just a bedtime story to me until my name was connected with the predictions. That is why I have not forgotten it all. I have rolled my eyes many times just thinking about grandfather today. I have witnessed many of his predictions that have happened in some parts of the world. Not only have I witnessed them with my eyes but have also felt them and have been affected by them. His predictions about the movements of the people around the world is something else. But that is another subject to be written about.

I am one of those scientists my people love to hate, those who occasionally arrive in the Arctic only at a certain season, therefore I am not acutely aware of changes that are taking place on the land. That may be true in many cases but you do not forget the land you grew up in. You do not disregard it just because you are away from it much of the time. In fact, you appreciate it more, the more you are away from it. You remember more acutely the way it was. In fact, each time I go back I go into shock to see how it is being treated.

Compared to Mini and Miki’s time, I have noted that now in the spring in the Arctic, the sun does not melt streams and little lakes like it used to, that it gets later and later in the season. Even snow and cold conditions get later and later. That the snow buntings are not there the usual time. That the berries do not even get time to ripen in certain parts of the Arctic. In fact, I was flying over James and Hudson Bays in the middle of June this year: both the bays were still covered with ice. My instinct told me that the southwest harsh wind had not come at the usual time. In talking with people and relatives I heard that the long stay of the ice created a lot of hardship for the traditional hunters. Usually by the end of June, their freezers are full of geese and ducks for summer and fall food supply. The basking seals were hard to go and get, even though there was lots of ice still out there, the ice was not thick enough to travel on safely by skidoo.
INSIGHTS OF A HUNTER ON RECENT CLIMATIC VARIATIONS IN NUNAVUT

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ABSTRACT
My talk to the workshop discusses the unpredictable weather in the North and my observations with regard to global change as it applies to the Arctic. The sun seems to be stronger than it used to be, especially this past spring when I noticed its strength during my big circle travel by snowmobile from Rankin Inlet to Baker Lake, Gjoa Haven, Spence Bay, Pelly, Repulse, Chesterfield Inlet and return. Lypsak didn't seem to have its usual strength, I compared this with two years ago when I took a long snowmobile trip between Rankin Inlet and Repulse Bay.

PRESENTATION
Distinguished delegation I come from Rankin Inlet of Nunavut where, last week, we were finally able to use our snowmachines. This was already one month later than they were able to start using them in Repulse Bay, 400 miles to the north.

I wonder if there is a conflict between the scientific knowledge of the experts and the traditional knowledge of the Inuit elders or whether in fact they are both the same. One body of knowledge is based on decades of experience, the other on the collection of scientific data.

Last July 18, 1991, in the Keewatin, the area west of the Hudson Bay, we had temperatures in the 30s for more than one month. On July 10, 1991 a friend and myself, my son and daughter, went caribou hunting on our ATV's. Along the way, we were amazed to notice that every small lake had scores of local people swimming. It was so hot that all day I hunted without a shirt.

We also stopped to swim. This was the first time in my life that such a thing had happened to me.

This summer, on July 10, 1992, I was wearing windpants and a down jacket to work on the outside of my house. Ice break-up was one month late in most of the communities and the freeze-up seems now to have come so early. The first barges for freight transportation, scheduled for the end of July, took until mid-August to get rolling due to the late break-up.

The statistics provided to me by Environment Canada indicate that the mean temperatures of July and August for the years 1989 and 1991 were indeed the highest for the past twelve years. This past summer, 1992 the temperatures were the lowest for the same 12 years.

The Roman Catholic Church representatives in Chesterfield Inlet, 80 miles to the north east of Rankin Inlet have been recording weather for the past 50 years. Their observations indicate that in the 1940s there were frequent readings of −55° and −60° Fahrenheit in the winter. That now in the 1980s and 1990s the lows are more like −45° & −50° Fahrenheit in the winter.

This summer for the first time large tracts of ice along the Meladine River System, just outside of Rankin Inlet, did not melt. All summer, residents have been able to collect ice in addition to the fresh water for drinking and making tea. With another cold summer next year will this be the beginning of permanent ice build-up?

The elders do tell us that once every so many years cool summers repeat themselves, that also some years have freak snow storms that occur in mid-summer. My father told me about one such year in his memory where there

1 Peter Ernnerk is the Executive Director of the Inuit Cultural Institute in Rankin Inlet. He has had a long term interest in northern environmental issues on a regional, national, and international level.
was such a cold and extended snow storm in the middle of an otherwise warm summer, that this storm caused many baby birds to die, that all the mosquitoes appeared to die off and there was quite an accumulation of snow on the ground. He remembered that after the storm was over the snow melted and things did return to normal. In discussing this particular storm with my boss, Ollie Ittinuar, who is presently 70 years old he indicated to me that he remembered that particular storm. My father was at least 25 years his senior and we place this storm in the early 1930s. It was the storm and summer to remember.

In our part of the world scientists had observed in 1980 that the caribou were decreasing, that the numbers were down to 37,000. They advised that hunting would have to be severely restricted to protect the herds from extinction. Inuit kept pointing out that the herds merely changed migration routes periodically and that they would reappear in years to come.

Suddenly in 1982 the caribou counts indicated a vast number of animals that had not been there previously, now the numbers were at 300,000 individuals. Now there was no longer a need for restriction of the hunting rights of the Inuit. Through their traditional knowledge the Inuit had known this. I assume that this is another example of the cyclical variations in the caribou population.

On a related matter, an observation that I made this spring, and it has been confirmed by other travellers, is that the sun seems to be “stronger”. Traditionally Inuit used animal oil and fat to protect lips from the rays of the sun and the wind, today we have lysol from the “Northern Store”. Traditionally we had bone glasses that reduced the glare of the sun to protect the eyes from snow blindness. Today we have a variety of “sun” glasses with assorted side protectors for the spring traveller. On an extended trip which I made this spring I found that contrary to other years these forms of protection were no longer adequate to protect me from the rays of the sun. Prior to my departure I purchased “Top of the Line” sun glasses with protective leather on the side, and I wore them religiously. Yet I spent several weeks upon my return seeing double due to the eye strain (and the check-up that I had at the optometrist proved that it was not yet my age catching up with me). Various nurses from the health centers have reported more burns, more sun allergies and sun sensitivities amongst the Inuit population.

In earlier years the dark skinned Inuk did not need to protect himself as much as the fair skinned, ‘Qablunaaq’ but this seems to be changing, even dark skinned Inuit are suffering from burns the way their southern friends do. Is this due to the global warming or to the thinning ozone layer that is also being observed and documented or a combination of both.

In spite of several summers being warmer than average we seem to have observed that the winters have been colder, and longer.

The scientists are telling us that this year the cold spell is due to the volcanoes in the Phillipines, to the accumulation of dust in the atmosphere. The elders are aware of the effects of such occurrences and that they repeat on some kind of regular pattern.

Is there really global warming overall or is the phenomena just the cyclical variations of the weather that has been observed by the elders and passed down for the knowledge of the next generation?

I hope that the brief time that I have shared with you, and my knowledge can contribute to your work in the field of global warming.
Global Warming?

OLLIE ITTINUAR
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With respect to the weather, I have observed the weather all my life, always trying to figure out its nature as it is part of our life. We the hunters continually observe the cold and the warmth of the weather, for me ever since I was born. I have done much of this all my life. Sometimes it is too hot and sometimes it is too cold after many years have passed. This summer (1992) it was not hot all summer – no vegetation grew, both ice and snow really didn’t melt. I have read that it is getting warmer. When is this going to become a reality?

1 Ollie Ittinar is an elder and the President of the Inuit Cultural Institute in Rankin Inlet. He wrote this letter for Peter Ernerk, who translated the Inuktut version into English.
BIOCLIMATIC IMPLICATIONS OF GLOBAL WARMING
FOR THE BOREAL AND SUBARCTIC
REGIONS OF WESTERN CANADA

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ABSTRACT
Scientists are certain that an important climatic change factor, the "greenhouse effect", is substantially increasing. Therefore, the probability of major global climatic change due to the enhanced greenhouse effect is also increasing. Unmitigated global warming could have significant effects on the circumpolar boreal forest and on subarctic regions. The objectives of this paper are to estimate possible effects of climatic change on bioclimate, and to assess the implications for the boreal and subarctic regions. Current climatic change scenarios indicate that ecosystem responses will be neither spatially nor temporally uniform, however, very few global warming impact assessment studies of the boreal and subarctic regions have been undertaken. Preliminary work shows that the ecoclimates of the parkland and southern boreal regions will move northward with climatic warming and this could be one of the first indicators of change in the subarctic region. It is very important to improve our understanding of the sensitivity of these environments and socioeconomic systems to climatic variations and to integrate climate change impact information into the planning process. Safe strategies to minimize the negative impacts and maximize the benefits of these changes are needed.

INTRODUCTION AND OBJECTIVES
Climatic change, including global warming, its possible impacts, and limiting and preparing for climatic change are central challenges for humanity. Scientists are certain that emissions resulting from human activities are substantially increasing the atmospheric concentration of the "greenhouse gases". These increases enhance the greenhouse effect, resulting on average in an additional warming of the Earth's surface (IPCC, 1990). Significant effects are expected for many human activities and resources, and the environment, including agriculture, forests, water resources, energy, tourism, human and animal health, and air quality.

A proactive strategic planning approach is required to deal with and to prepare for climatic change and variability. We must minimize the losses and maximize the benefits of climatic change. Important concerns and questions include: what is the range of possible future climates; what are the consequences of climatic change; how do we limit the change; and what are the best ways to prepare for and adapt to climatic change?

1 Elaine Wheaton is the lead scientist of the Climatology Section of the Saskatchewan Research Council. Her research includes climatic impact and adaptation assessments and dust storm climatology. She is a member of the Board of Directors of the Royal Canadian Geographical Society, the Canadian National Committee of the International Geographical Union, and the Editorial Board of the Climatological Bulletin, and has several other affiliations.

2 Virginia Wittrock is research scientist in the Climatology Section of the Saskatchewan Research Council. Her research includes climatic impact and adaptation assessments. She is a member of the Executive of the Water Studies Institute, of the Executive of the Saskatchewan Chapter of the Canadian Parks and Wilderness Society, and of the Saskatchewan Branch of the Canadian Water Resources Association and other associations.
The study area is the boreal forest and subarctic regions of interior western Canada (Figure 1). Additional reasons for concern for the study area include:

1) the boreal forest region is quite sensitive to climate (e.g. Singh and Wheaton, 1991);

2) warming is predicted to be 50 to 100% greater than the global mean in high northern latitudes in winter (IPCC, 1990: xxiii); and

3) changes in the boreal ecosystem, in turn, have the potential to change climate through feedback mechanisms such as carbon sequestering, methane emissions and through changes to the microclimate. These risks emphasize the need to assess the implications of climatic change for the boreal forest.

Many studies have related forest characteristics, especially productivity and zonation, to climate. However, few have examined the potential impact of global warming on the boreal forest ecosystem (Wheaton, 1992). Preliminary work shows that the ecoclimates of the parkland and southern boreal regions will move northward with climatic warming (e.g. Singh and Wheaton, 1991). This could be one of the first indicators of change in the subarctic region.

The study objectives include:

1) estimating the possible effects of climatic change on a bioclimatic index;

2) exploring the seasonal and spatial changes in a bioclimatic index; and

3) assessing the implications for the boreal and subarctic boreal regions.

METHODOLOGY

The methodological approaches for climatic change impact assessments are in their infancy and standardization of approaches is lacking (Cohen, 1990). The main steps are as follows and are used here:

1) development or specification of global warming scenarios for the study area;

2) development or specification of impact models; and

3) application of the scenario(s) to the impact model(s).

Development of a Climatic Change Scenario

The General Circulation Model (GCM) used to develop the climatic change scenario used here is the Canadian Climate Centre's 1990 version, second generation GCM (CCC GCMII) (CCC, 1990). The use of more than one climatic change scenario is recommended because of the uncertainties surrounding the estimates of regional climatic change and for sensitivity analyses. Only one scenario could be used here, however, Wheaton et al. (1987) provide results using other GCM experiments and the same impact model. Other GCM results that were used in Wheaton et al. (1987) were the ones
from the Goddard Institute for Space Studies and from the Geophysical Fluid Dynamics Laboratory.

The following procedure was used to develop a climatic change scenario for the study area:
1) CCC GCMII grid points and suitable climatic stations closest to these grid points were located on the study area map (Figure 1);
2) For each of the grid points, the change in mean monthly temperature was calculated as the difference between the 2xCO$_2$ and the 1xCO$_2$ GCM results. The ratio of these GCM runs were used to calculate the change in mean monthly precipitation; and
3) Changes in the monthly mean values derived in step number (2) were then applied to the baseline mean climatic data (1951 to 1980 normals) for each station from Environment Canada (1982). The climatic network is very sparse in the study area, so several grid points did not have a nearby climate station. Normal monthly temperature, precipitation and solar radiation data for these points were interpolated from normal maps (Environment Canada, 1984, 1986, 1987). Solar radiation was assumed to remain as for the baseline climate.

One of the first studies to use this procedure of applying the ratios or differences to baseline climatic data to develop climatic change scenarios was Williams et al. (1988). It has become convention for most climate change impact assessments.

GCM grid point results represent areal averages, not point values of the grid squares centered on the point. Therefore, possible mismatches between GCM output and even the near station data can exist, especially with complex terrain or strong climatic gradients (CCC, 1990). The study area's topography is not complex, so this problem may not be as pronounced.

**Bioclimatic Analyses**

This section introduces the concept of bioclimatic analyses with an emphasis on a specific model. Although climatological elements are often described separately in climatic descriptions, the combination of climatic parameters, rather than the elements acting singly, has a major effect on plant growth and production. The relation of vegetation and weather and climate can be assessed by such climatic indices.

The climatic index chosen for analyses for these purposes is the "climatic index of agricultural potential" or CA (Turc 1968). It is chosen for several reasons, including the authors' previous experience with it, good correlation with vegetation, and its data requirements. It is an indicator not only of the agricultural potential of the climate, but also of the potential for biomass productivity in general, including forests and it is not limited to one vegetation type (Turc and Lecerf, 1972). The term biomass productivity is used as equivalent to total harvestable dry matter, which includes the weight, after drying, of all harvestable plant material. Another advantage of CA is that it can be used to explore changes in biomass zonation. Considering that climatic change may be accompanied by a shift in vegetation zones, this capability is useful, and perhaps even necessary.

CA combines thermal, radiation and moisture parameters. It is computed by summing the 12 monthly products of heliothermic and soil moisture factors. The heliothermic factors reflect both temperature and solar parameters. The soil moisture factor uses both precipitation and temperature in a climatic soil moisture budgeting procedure.

Monthly and annual values of CA were computed for grid points in the study area for the CCC GCMII scenario and for the historical normals for the stations shown in Figure 1. CA has not been verified against forest growth and yield data for the study area. Therefore, the differences between the CA calculated for the future climate scenario and that for the present climate is used to assess the possible relative change. CA is not intended to provide an exact measure of bioclimatic potential, but to explore the direction and relative magnitude of change.
RESULTS

Climatic Change Scenario

The climatic change scenario was originally developed for the Wheaton, Wittrock and Williams (1992) work and was extended northward for this work. The temperature and precipitation characteristics of the scenario for the Saskatchewan portion of the study area are described in Wheaton et al. (1992) so only some of the highlights are noted here. 

Temperature: For the subarctic region (Figure 1) the largest increases of temperature are in winter, in December (about 10°C), and the second largest increase is in March (9°C). The lowest increases occur in the spring (April) and fall (October) at about 1 to 2°C. For most months the largest increases spatially are in the eastern parts of the study area. 

For the boreal region, the largest increases are usually in December (about 11°C), as well as February, and the lowest increases are for spring and fall.

Precipitation: For the subarctic region, there is a predominance of increases, especially for the May to November period (many in the 15 to 35% range). However, there are notable decreases, especially for the western grids and for winter (January and February).

Larger changes, as both increases and decreases, are simulated for the boreal region as compared to the subarctic region. The decreases are mostly in late winter and early spring (February and March) as well as some decreases for the summer months.

Implications of Global Warming for Climatic Potential for Biomass

What ecosystem responses would be expected from these types of precipitation and temperature changes? One way to approach this question is to examine the changes in a bioclimatic index such as CA. Changes in CA for the climatic change scenario as compared to the baseline climate are shown across three grid point transects across the study area (Figure 2). These are: the northern transect across the subarctic region from Fort Resolution to Ennadai Lake, including two estimated (for the baseline climate) points; the central transect from an estimated point in Alberta to Embaras through Saskatchewan points to Brochet and another point in Manitoba; and a southern transect from White Court, Alberta across Saskatchewan to Norway House, Manitoba.

General patterns of CA changes from baseline for climatic change for the boreal and subarctic regions generally appear as increases (Figure 2). The increases are especially pronounced in May, June and September with some decreases mostly in July and August. For example, Brochet's June CA increase is 1.7, which is 27.5% above normal. This pattern indicates that a lengthening of the growing season into the shoulder seasons of spring and fall, as well as a strengthening of spring and fall bioclimatic potential would be expected.

In contrast to the strengthening of CA in the ends of the growing season, decreases in CA appear for July and August. June decreases are found for Embaras in the northern boreal location. These decreases indicate constraints to biomass productivity.

Examples of spatial patterns are noticeable. The summer decrease in CA appears to affect more points in the subarctic region than in the boreal region. The southern transect experiences increases in early spring (April) and late fall (October) for some points, while no noticeable changes occur farther north during these times.

CONCLUSIONS

In summary, although the growing season lengthens with climatic warming as simulated by the CCC GCMII based scenario, summer constraints to biomass productivity are also found. The summer constraints are most common for the northern transect across the subarctic region. This is an unexpected result as the temperature constraints are thought to be increasingly limiting farther north and that the bioclimate would benefit with warming.

This use of the bioclimatic index is in its preliminary stages. Therefore, several recommendations can be formed:

1) CA should be verified against growth and yield data for the study area. Such
work should lead to further insights and understanding of the ecosystem responses to climate;

2) Improvements in CA could be made based on this verification; and

3) Bioclimatic models should be used in combination with other models to explore combined effects of changes in climate and disturbance factors such as insects, diseases, and fires. Synergistic effects are expected and should also be explored.

It is hoped that this use of a bioclimatic index will not only provide early warnings of possible ecosystem changes, but also improve the understanding of ecosystem responses to climate. This understanding appears to be embryonic, so such preliminary work needs to be improved to provide better warnings. Safe strategies must be developed to minimize the negative impacts and maximize the benefits of these changes.

REFERENCES CITED
Canadian Climate Centre (CCC), 1990. 
Application of the Canadian Climate Centre General Circulation Model Output for Regional Climate Impact Studies – Guidelines for Users. CCC, Downsview, Ontario.


Figure 2a
Bioclimatic Change
Central Transect

Figure 2b
Bioclimatic Change
Northern Transect

Figure 2c
Bioclimatic Change
Southern Transect

Figure 2 Seasonal changes in bioclimatic productivity with climatic change as indicated by CA (the Climatic Index of Agricultural Potential) for three west to east transects: a) northern transect, b) central transect and c) southern transect. Est = estimated point (for the baseline climate).
POTENTIAL IMPACTS OF A CO$_2$-INDUCED CLIMATE CHANGE ON HYDRO-GENERATION CAPACITY OF SEVERAL RIVER BASINS IN NORTHERN QUEBEC

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ABSTRACT

Because of increasing emissions of radiatively active gases (RAGS) over recent time, the greenhouse mechanism of the atmosphere and the earth’s radiation budget is expected to change, so much so as to produce significant changes in climate within the next 50 to 100 years.

One of the most expedient and popular methods to detect this climate change is through use of general circulation models (GCM). Most present-day GCM’s derive expected changes in climate through equilibrium solutions of the equations for the exchanges of energy, mass and momentum, and for the idealized gas law. Transient solutions are not presently well-developed. There are a host of GCM’s in use and existence today, including GFDL, GISS, UKMO, OSU, NCAR, and CCC. Limited area (LAM) versions of these models are beginning to appear and they will be of great use in regional scale impact studies.

In this study we used the GFDL, GISS, OSU and in particular the high resolution CCC model to evaluate the impacts of climate change on hydro-electric power production in northern Quebec.

Changes in net basin supply (NBS) and river flow are used to gauge the changes in hydro-generating potential of a number of drainage basins in northern Quebec, including the Baie James and Grande Baleine basins.

Results vary with climate change scenario. However, the high resolution CCC model points to a decrease in river flow and hydro-generating potential for most drainage basins.

INTRODUCTION

Because of the increasing rate of emissions of greenhouse gases and land use changes such as deforestation, the atmospheric composition of such gases as CO$_2$, CH$_4$, N$_2$O, O$_3$, and CFC’s are increasing at an alarming rate, so much so as to cause a doubling of their combined concentration by the year 2050 to 2100 (WMO, 1986; IPCC, 1990).

An effective doubling of CO$_2$ concentration would very likely bring about large perturbations in the present-day climate, notably an increase in temperature and absolute humidity within the near-surface air layer (Kellogg, 1979; Watts, 1980; Berger, 1981; Clark, 1982; Manabe, 1983; Flohn and Fontechi, 1984), a decrease in net terrestrial and global solar and hence net radiation (Ramathan, 1981; Chou et al., 1982) and modifications in nebulosity and in the annual regime of precipitation (Manabe et al., 1981; Washington and Meehl, 1983, 1984; Mitchell, 1983, 1986).

Furthermore, these changes of key climatic parameters would undoubtedly influence such

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\textsuperscript{2} Pierre-David Trudel recently (June 1992) completed his Masters Degree at the Université de Montréal on the potential impacts of climate change on river flow and hydrogenerating potential in Northern Quebec. He is currently pursuing his doctoral studies at CARTEL, University of Sherbrooke, on evaluating global change using remote sensing methods.
hydrological variables as evaporation or evapotranspiration, soil moisture, ground water storage and stream flow (Bultot et al., 1988a, 1988b; Mitchell, 1989; Thompson, 1992). A CO₂-induced climate change could therefore have a significant impact on such water-resource-based industries as hydro-electric power generation, that is critically dependent upon precipitation and stream flow (Bruce, 1984; Sanderson et al., 1985; Howe et al., 1986; Cohen, 1987; Singh et al., 1987; Singh, 1987; Frederick and Gleick, 1988).

It is our intent in this paper to focus upon the potential impacts of a CO₂-induced climatic change on the components of the water balance, notably surface run-off, and how these modifications would conceivably influence the hydro-electric generating potential of several river basins in Québec. This inquiry is of major importance, since hydro-electric power generation is a key component of the Québec economy.

**METHODOLOGY**

Several studies have previously used CO₂-induced climate change scenarios to evaluate the hydrological impacts at the regional or basin scale (Bruce, 1984; Sanderson et al., 1985; Howe et al., 1986; Cohen, 1986, 1987; Singh et al., 1987; Singh, 1987; Gleick, 1987a, 1987b; Bultot et al., 1988a, 1988b; Armel et al., 1990). In this paper, we examine the potential impacts of a CO₂-induced climate change on the net basin supply (NBS) of eight river basins within the province of Québec that are used or projected to be used for hydro-electric power generation. These are Betsiamites, Gatineau, St.Maurice, Outardes, La Grande, Churchill, Nottaway-Broadback-Rupert (NBR), and Grande Baleine (Fig. 1).

The climate change scenarios that we selected for this study, based on data availability, are the General Fluid Dynamics Laboratory (GFDL) (Manabe and Wetherald, 1975; Manabe and Stouffer, 1980) and the Goddard Institute for Space Studies (GISS) (Hansen et al., 1983), the Oregon State University (OSU) (Ghan et al., 1982; Schlesinger and Zhao, 1988), and the Canadian Climate Centre (CCC) (Boer et al., 1992; McFarlane et al., 1992) General Circulation Models (GCM's). The spatial resolutions of these GCM's are: 4.44° Lat. by 7.5° Long. (GFDL), 7.83° Lat. by 10° Long. (GISS), 4° Lat. by 5° Long. (OSU), and 3.75° Lat. by 3.75° Long. (CCC) respectively. These GCM's provide model outputs of monthly air temperature (°C), precipitation (mm/day), incident global solar radiation (W/m²), wind speed (m/s), cloud cover (%), run-off (mm/day) and humidity (%) for a 1 x CO₂ and a 2 x CO₂ atmosphere. The CCC also provides net radiation (W/m²), evaporation (mm/day) and soil moisture (mm).

**FIGURE 1. Distribution of GCM grid points and drainage basins for this study.**

For the eight drainage basins selected, NBS was calculated for both the 1 x CO₂ and the 2 x CO₂ scenarios using the appropriate outputs from the four GCM's namely, GFDL, GISS, OSU, and CCC.

The general formulation of the equation for calculating NBS for drainage basins consisting of both land and open lake and reservoir surfaces may be written as:

\[ \text{NBS} = (\text{Land run-off} \times \text{Land area}) + [(\text{P}_{\text{lake}} - \text{E}_{\text{lake}}) \times (\text{Lake area})] - \text{Consumption} \]  \hspace{1cm} (1)

NBS is expressed in M³S⁻¹, Pₗₐₗₖₑ represents total precipitation falling on the lake and reservoir surfaces (mm/year) and Eₗₐₜₑ represents the total
evaporation from the lakes and reservoirs (mm/year).

In our analysis, land run-off was calculated as the surface discharge or water surplus (mm) using the Thornthwaite monthly water budget method (Thornthwaite, 1948; Thornthwaite and Mather, 1955, 1957), expressed as:

\[ R_o = P - AE \pm \Delta St \]  \hspace{1cm} (2)

\( R_o \) is the monthly surface run-off (mm), \( P \) is the monthly precipitation (mm) and \( AE \) is the actual monthly evaporation and evapotranspiration (mm), as regulated by air temperature and soil moisture and, \( \Delta St \) is the monthly change in soil moisture (mm). Based on our knowledge of the average soil depth of the region (Singh and Taillefer, 1984) and on values cited elsewhere for similar regions (Cohen, 1986, 1987; Howe et al., 1986), a value of Water Holding Capacity (WHC) of the soil layer equal to 100mm was used.

We also assumed that the consumption term of equation (1) to be zero. This is justifiable for the northerly basins near James Bay and Labrador, namely La Grande, NBR, Churchill, and Grande Baleine because of their remoteness and sparse populations, and because very little water is consumed in hydro-electric power generation. However, for the southerly basins that drain into the St. Lawrence river, namely Betsiamites, Gatineau, St. Maurice and Outardes, where population is somewhat important, this assumption could lead to some error in our calculations. Also damming operations, which caused the creation of artificial reservoirs and expansion of lake surfaces and which took place during the normals period (1961-1990), should not significantly influence the calculations of equation (1) (Singh, 1987).

Precipitation falling on lakes and reservoirs was assumed to be equal to that falling on land, unlike other studies (Cohen, 1986a, 1986b) since individual lake and reservoir surfaces are relatively small.

Lake evaporation (\( E_{lake} \)), on the other hand, was estimated firstly, according to the Priestley-Taylor equation (Priestley and Taylor (1972), written as:

\[ E_{lake}^{(1)} = \left\{ \alpha \frac{(S/S + \gamma)}{(Q^* - QG)} \right\} / L \]  \hspace{1cm} (3)

Alternatively, lake evaporation (\( E_{lake} \)) was calculated using the Bowen ratio-energy balance (BREB) technique, as follows:

\[ E_{lake}^{(2)} = \frac{(Q^* - QG)/L}{1 + B} \]  \hspace{1cm} (4)

with the Bowen ratio, \( B \), derived as (Lafluer and Rouse, 1988):

\[ B = 3.61 \exp(-0.1643 T) \]  \hspace{1cm} (5)

\( E_{lake}^{(1,2)} \) is the monthly lake evaporation (mm), \( Q^* \) is the net radiation (MJ M\(^{-2}\) month\(^{-1}\)), \( QG \) is the soil heat flux (MJ M\(^{-2}\) month\(^{-1}\)), \( S \) is the slope of the saturation vapor pressure curve (Pa C\(^{-1}\)) calculated from air temperature, \( \gamma \) is the psychrometric constant (0.066 x 10\(^3\) Pa C\(^{-1}\)), \( \alpha \) is a non-dimensional surface evaporability factor, \( B \) is the Bowen ratio, \( T \) is air temperature (°C) and \( L \) is the latent heat of vaporisation (MJ Kg\(^{-1}\)).

Except for the CCC, which directly calculates the net radiation, \( Q^* \) was determined from the values of global solar radiation (K J) as follows (Oke, 1987; Renaud and Singh, 1989):

\[ Q^* = K \cdot 0.9 \]  \hspace{1cm} (6)

Similarly, except for the CCC, which provides values of the soil heat flux (QG), \( QG \) is derived as (Oke, 1987; Renaud and Singh, 1989):

\[ QG = Q^* \cdot 10 \]  \hspace{1cm} (7)

For \( \alpha \), we chose to use the large-scale value of 1.26 as recommended by Stewart and Rouse (1977) for lake surfaces. Advection effects, as cautioned by Singh and Taillefer (1986) are ignored.

Monthly values of run-off, precipitation, and evaporation are summed to derive annual totals. Also in equation (1), since land run-off and \( P_{lake} - E_{lake} \) are in mm year\(^{-1}\) and land and lake area are in Km\(^2\), each half of the equation, neglecting consumption, was multiplied by 31.71 x 10\(^6\) so that the final units of NBS are in m\(^3\) S\(^{-1}\), since these are the units needed to derive hydro-generating capacity.

Because of the coarse spatial resolution of the GCM grid points and because of the sub-grid size of the basins, we chose the grid point within the periphery of each basin when possible or when not the case, the grid point that is closest to the drainage basin (Fig. 1).

Measured mean annual discharge for the normals (1961-1990) period (NBS\(_o\)) are then compared to the 1 x CO\(_2\) scenarios of NBS (NBS\(_1\)). In turn NBS for 1 x CO\(_2\) (NBS\(_1\)) are com-
pared with NBS for 2 X CO₂ (NBS₂) to derive percent changes in NBS (ΔNBS). We then adjusted observed NBS (NBS₀) by an amount equal to Δ NBS (NBS₂-NBS₁) so as to derive the final change in NBS (NBS₃) as

\[ \Delta \text{NBS} = \text{NBS}_2 - \text{NBS}_1 \]  
and \[ \text{NBS}_3 = \text{NBS}_0 \pm \Delta \text{NBS} \]  

Hydro-generating potential (KW) is derived by multiplying NBS (m³/s¹) by the appropriate production factor (PF : KW m³/s¹) as furnished by Hydro-Québec. The production factor (PF) is a function of the type of turbine and an optimum reference water fall height. NBS₀ and NBS₃ are then multiplied by PF to give the 1 x CO₂ (NBS₀ x PF) and 2 x CO₂ (NBS₃ x PF) generating potentials.

Also, since there can be several generating stations within a drainage basin, these calculations are done at each installation and are then summed to provide total basin generating potential.

**RESULTS**

Our results focus firstly on the comparisons between observed discharge (NBS₀), and NBS for the 1 x CO₂ scenario (NBS₁) and between NBS, and NBS for the 2 x CO₂ scenario (NBS₂). These comparisons are performed for each of the GCM's, namely GISS (Table 1a), GFDL (Table 1b), OSU (Table 1c) and CCC (Table 1d).

The GIIS scenario provides data that meet our criteria for the Betsiamites, Outardes, NBR and Churchill basins (Table 1a). Of these, only Betsiamites has a grid point that falls within the basin limits. NBS₀ and NBS₁ are reasonably close for the Outardes (15.2%), Betsiamites (27%) and Churchill (31%) basins, whereas for the NBR basin NBS₁ underestimates by 63.4% (Table 1a).

Even as such, the changes in NBS (ΔNBS) show increases for the larger and more northerly basins such as NBR (24.6%) and Churchill (7%) and decreases for the smaller and more southerly basins such as Betsiamites (−4.5%) and Outardes (−2.9%) (Table 1a).

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Gatineau</th>
<th>St-Maurice</th>
<th>Betsiamites</th>
<th>Outardes</th>
<th>NBR</th>
<th>La Grande</th>
<th>Churchill</th>
<th>Grande Basine</th>
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<tbody>
<tr>
<td>Surface area</td>
<td>2223 sqm</td>
<td>2734 sqm</td>
<td>4785 sqm</td>
<td>11380 sqm</td>
<td>24678 sqm</td>
<td>26328 sqm</td>
<td>7146 sqm</td>
<td>2300 sqm</td>
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<tr>
<td>% of lake and reservoir area</td>
<td>9.3%</td>
<td>8.6%</td>
<td>9.4%</td>
<td>60.4%</td>
<td>20.2%</td>
<td>26.1%</td>
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<tr>
<td>NBS [m³/s]</td>
<td>369</td>
<td>462</td>
<td>429</td>
<td>705</td>
<td>2348</td>
<td>2617</td>
<td>1852</td>
<td>1194</td>
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<td>NBS [m³/s]</td>
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<td>2348</td>
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<td>1194</td>
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<tr>
<td>Difference NBS and NBS [m³/s]</td>
<td>97 [64.5%]</td>
<td>13 [2.9%]</td>
<td>215 [24.8%]</td>
<td>1231 [10.7%]</td>
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Table 1a. Net basin supply (NBS) calculations for the different drainage basins according to GISS scenario (shaded boxes: grid points within basins).

The GFDL scenario yields acceptable data for all eight of the drainage basins (Table 1b). Differences between NBS₀ and NBS₁ are reasonable for the most southerly basins, namely St. Maurice (−12.6%) and Gatineau (−13.9%) and possibly for Churchill (33%) of the northerly basins (Table 1b).

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Gatineau</th>
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Table 1b. Net basin supply (NBS) calculations for the different drainage basins according to GFDL scenario (shaded boxes: grid points within basins).
As for the change in net basin supply, (ΔNBS) all basins except NBR (−6.5%) show an increase in NBS ranging from 2.2% (La Grande) to 11.4% (St. Maurice) (Table 1b).

The OSU scenario also provides acceptable data for all of the drainage basins with grid points falling within the Betsiamites and Churchill basins (Table 1c). Also differences between NBS0 and NBS1 again seem reasonable for the most southerly basins, namely St. Maurice (−19%), and Gaineau (−19.3%) and possibly Churchill (−30.9%) for the northerly basins (Table 1c). It would also seem the OSU scenario (NBS1) consistently underestimates the observed discharge (NBS0).

Finally, the high resolution CCC, not surprisingly, provides reliable data for all drainage basins with grid points falling within the La Grande and Churchill basins (Table 1d). Also, NBS3 compares favorably with NBS0 for Outardes (25.4%) of the southerly basins and for NBR (−2.3%), La Grande (−9.6%) and Churchill (24.8%) of the northerly basins (Table 1d).

However, insofar as ΔNBS is concerned, all basins show a decrease in ANBS except for Grande Baleine (4.7%) with values ranging from −2.8% (La Grande) to −12.8% (Outardes) (Table 1d).

The changes in hydro-generating potential are now discussed. Tables 2a, 2b, and 2c provide values of hydro-generating potential for the 1 x CO2 scenario (NBS0 x FP), the 2 x CO2 scenario (NBS2 x FP), the change in generating potential (NBS2 x FP – NBS0 x FP) for each generating station and each GCM and the total change in generating potential with respect to each drainage basin and GCM.

<table>
<thead>
<tr>
<th>River basins</th>
<th>Hydro-</th>
<th>Turbine</th>
<th>GCM*</th>
<th>Σ Total of GCM* (kW)</th>
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<td>NBS0 x FP</td>
<td>NBS0/FP</td>
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</table>

1. Weighted value of NBS0.  
2. Weighted value of NBS0 for different GCM.

Table 2a. Changes in NBS (m3/s) and hydro-generating potential (kW) for the different GCM scenarios for the Gaineau and Saint-Maurice river basins.

<table>
<thead>
<tr>
<th>River basins</th>
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<th>Turbine</th>
<th>GCM*</th>
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<td>Rivière Outardes</td>
<td>electric</td>
<td>capacity</td>
<td>NBS0 x FP</td>
<td>NBS0/FP</td>
</tr>
<tr>
<td>NBS0 (m3/s)</td>
<td>central</td>
<td>(kW)</td>
<td>(kW)</td>
<td>(kW)</td>
</tr>
<tr>
<td>NBS1 (%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GFOL 43.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOU 477 +15%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CCC 79.8 +15%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rivière Outardes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>401 (367)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>1371</td>
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<td>371</td>
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<tr>
<td>125 101</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>GFOL 43.0</td>
<td></td>
<td></td>
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<tr>
<td>SOU 477 +15%</td>
<td></td>
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</tr>
<tr>
<td>CCC 79.8 +15%</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

1. Weighted value of NBS0.  
2. Weighted value of NBS0 for different GCM.

Table 2b. Changes in NBS (m3/s) and hydro-generating potential (kW) for the different GCM scenarios for the Betsiamites and Outardes river basins.
Table 2a presents the change in hydro-generating capacity for the smaller and most southerly drainage basins of Gatineau and St. Maurice. These results show that according to the GFDL and OSU scenarios, hydro-generating potential may increase by 5,698 KW (OSU) to 31,564 KW (GFDL) annually for the Gatineau basin and by 31,390 KW (OSU) to 102,514 KW (GFDL) annually for the St. Maurice basin. On the contrary the CCC scenario projects a drop in hydro-generating potential of −8,228 KW for Gatineau and −72,112 KW for St. Maurice annually.

Table 2b presents hydro-generating capacities for the smallest and elongated basins namely Outardes and Betsiamites. In both cases, the GFDL and OSU scenarios project an increase in generating potential: 37,590 KW (GFDL) and 83,991 KW (OSU) annually for Betsiamites and 64,623 KW (GFDL) and 234,516 KM (OSU) annually for Outardes.

<table>
<thead>
<tr>
<th>River basin</th>
<th>Hydro-generating capacity (KW)</th>
<th>Turbine capacity (kw)</th>
<th>NBS, x FP factor</th>
<th>GCM</th>
<th>Total of GCM (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rivière La Grande</td>
<td>97,750</td>
<td>780 658</td>
<td>GFDL=17 760 kw</td>
<td>OSU=20 451 kw</td>
<td>CCC=21 939 kw</td>
</tr>
<tr>
<td>NBS, 1777 (m²/a)</td>
<td>LG4</td>
<td>1777 x 1044.7</td>
<td>GFDL = 48 797 kw</td>
<td>OSU = 34 146 kw</td>
<td>CCC = 39 556 kw</td>
</tr>
<tr>
<td>NBS, (%)</td>
<td>15%</td>
<td>10%</td>
<td>7%</td>
<td>11%</td>
<td>7%</td>
</tr>
<tr>
<td>GFDL = 34 146 kw</td>
<td>OSU = 34 146 kw</td>
<td>CCC = 39 556 kw</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GFDL = 48 797 kw</td>
<td>OSU = 48 797 kw</td>
<td>CCC = 48 797 kw</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CCC = 39 556 kw</td>
<td>OSU = 39 556 kw</td>
<td>CCC = 39 556 kw</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LG2</td>
<td>1777 x 1272.7</td>
<td>GFDL = 40 635 kw</td>
<td>OSU = 51 050 kw</td>
<td>CCC = 48 635 kw</td>
<td></td>
</tr>
<tr>
<td>NBS, 1777 (m²/a)</td>
<td>1777</td>
<td>1272.7</td>
<td>GFDL = 40 635 kw</td>
<td>OSU = 51 050 kw</td>
<td>CCC = 48 635 kw</td>
</tr>
<tr>
<td>NBS, (%)</td>
<td>15%</td>
<td>10%</td>
<td>7%</td>
<td>11%</td>
<td>7%</td>
</tr>
<tr>
<td>GFDL = 40 635 kw</td>
<td>OSU = 40 635 kw</td>
<td>CCC = 40 635 kw</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GFDL = 51 050 kw</td>
<td>OSU = 51 050 kw</td>
<td>CCC = 51 050 kw</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>GFDL = 48 635 kw</td>
<td>OSU = 48 635 kw</td>
<td>CCC = 48 635 kw</td>
<td></td>
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</tr>
</tbody>
</table>

1. Weighted value of NBS.
2. Weighted value of NBS for different GCM.

Table 2c: Changes in NBS (m²/a) and hydro-generating potential (kw) for different GCM scenarios for the La Grande and Churchill river basins.

Finally, Table 2c gives hydro-generating capabilities for the two largest northerly basins, namely La Grande and Churchill. For the La Grande basin, GISS data is missing. However, both the GFDL (86,979 KW) and OSU (1,034,144 KW) scenarios project an increase in hydro-generating capacity. On the other hand, the CCC model (−110,970 KW) shows a decrease in hydro-generating potential.

As for the Churchill river basin, both the GISS (283,041 KW) and GFDL (303,054 KW) scenarios project an increase, whereas the OSU (−114,360) and CCC (−231,579) show a decrease in hydro-generating potential.

It should be noted that no data pertaining to hydro-generating capabilities are presented for the NBR and Grande Baleine river basins. This is because of the fact that these basins have not as yet been developed for hydro-electric power production. If, however, one were to assume a more or less linear relationship between NBS (NBS₀, NBSₙ) and hydro-generating potential (KW), as seems to be the case for the other drainage basins (Tables 2a, 2b, and 2c), then one can safely assume that changes in hydro-gener-


Schlesinger, M.E. and Tao, Z., 1988. Seasonal climate changes induced by doubled CO$_2$ as simulated by the OSU atmospheric GCM / mixed-layer ocean model, CKI report. 84 p.


POST LITTLE ICE AGE WARMING AND
THE WESTERN CANADIAN BOREAL FOREST:
AN ANALOGUE FOR FUTURE CLIMATE CHANGE?

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Hamilton, Ontario
L8S 4K1

ABSTRACT

Dendrochronological records can provide evidence of the response of the boreal forest to episodes of climatic change that occurred in the recent past. This information is useful in providing empirical evidence on the potential impact of future climate warming and indicating if the present conditions of the forest represent a steady baseline against which to measure future climatically induced changes. In this paper we illustrate the use of dendrochronological records to examine the impact of post Little Ice Age warming on the boreal forest of western Canada. Our preliminary analysis of dendrochronological records from Picea mariana along the Kazan River and Picea glauca in the Mackenzie Mountains suggests that both the radial growth rates and recruitment increased markedly during the period between 1880 and the 1940s. Analysis of stand age data from Wood Buffalo National Park suggests that fire frequencies increased between 1882 and 1954. These changes are coincidental with hemispheric and local temperature increases recorded in instrumental records. However, other variations are present in radial growth, recruitment and fire frequency that suggest more complex relationships between temperature and forest conditions. Our data suggest that the forest has been profoundly affected by climatic variation following the Little Ice Age and that the present stands

INTRODUCTION

It is possible that by AD 2050 the average temperature of the earth will increase between 1.5 and 4.5 °C (Mackraken et al., 1990). The amplitude of this warming will likely be greater at higher latitudes with boreal regions in western Canada experiencing a warming of 2 to 10 °C during the winter and 2 to 8 °C during the summer (Mackraken et al., 1990). Such changes could potentially have major impacts on tree growth rates, forest distribution, and fire frequency (Emanuel et al., 1985; Solomon, 1986; D’Arrigo et al., 1987; Pastor and Post, 1988; Bonan et al., 1992; Flannigan and Van Wagner, 1991; Prentice et al., 1991; Rizzo and Wilken, 1992). In turn, changes in the distribution of boreal forest could themselves cause climatic changes (Bonan et al., 1992).

The sensitivity of the western Canadian boreal forest to climate change generates an urgent need for information on baseline conditions such as plant growth rates, regeneration patterns, and disturbance regimes. Without information on the current state of the forest it

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4 Kursti Dale has her B.Sc. (1992) from McMaster University in the Department of Geography.
line in northern Quebec (Payette and Filion, 1985; Payette et al., 1989). Studies there indicate that post Little Ice Age warming resulted in increased stand density accompanied by shifts from krummholz to tree growth forms.

**FIRE FREQUENCY IN THE CENTRAL BOREAL FOREST**

The rate of vegetation change during adjustment to greenhouse warming will likely be linked to the frequency of vegetation disturbance (Overpeck et al., 1990). The most important form of vegetation disturbance in the western Canadian boreal forest is fire (Johnson, 1992). Fire activity increases due to both reductions in precipitation and increases in temperature which, respectively, directly and indirectly result in increased fuel dryness (Kiil et al., 1977; Flannigan and Harrington, 1988; Balling et al., 1992a). Warmer summer temperatures due to global warming could therefore generate increased dryness and promote burning (Flannigan and Van Wagner, 1991; Balling et al., 1992b). However, if increased temperatures are coupled with greater precipitation, it is possible that there may only be negligible increases in fire activity.

**Study Site**

Wood Buffalo National Park (WBNP) is located in the central portion of the boreal forest (Fig 2). The park is 44 807 km² in size and lies between approximately 58⁰ and 60⁰ 45' N, straddling the Alberta – Northwest Territories border. Approximately one-half of WBNP is covered in lowland *Picea mariana* and *Sphagnum* bogs on low lying post-glacial clay deposits. The other half of WBNP is dominated by mixed and pure forests primarily of *Picea glauca*, *Populus tremuloides* and *Pinus banksiana* on moderately and well drained upland soils. Climate normals are available for Fort Smith, N.W.T. at 60° N on the eastern edge of the park. For the period between 1951 and 1980 the average mean annual temperature was −3 °C; the average yearly precipitation was 370 mm, with 220 mm falling as rain and 150 mm falling as snow (Environment Canada, 1982).

**Methods**

The fire history study was conducted by dividing WBNP into 165 equally sized sample units. A sampling point was positioned randomly in each unit and visited. At each sample point the time since the last fire in that stand was estimated by taking discs or increment bores from 5 to 10 of the tallest trees. The sample ages were typically clustered, and the oldest sample age in the cluster was taken to indicate the time since the last fire. The stands ranged from 4 to 305 years in age. For this analysis, only the data from stands established since 1850 are shown.

The percent of the landscape of each age (time since the last fire) was calculated. These percentages were then cumulated, with 100% occurring in the most recent fire year. Because older stands are lost randomly through time due to later fires, cumulative percent stand age frequency distributions often exhibit a negative exponential form (Van Wagner, 1978; Johnson and Van Wagner, 1985). When cumulative percent stand age frequency distributions are plotted on a logarithmic scale the time periods during which fire frequency was similar are indicated by a straight line plot through these scaled data (Johnson and Van Wagner, 1985). The slope of these lines can then be used to estimate the average annual area burned. The inverse of the annual percent area burned is the fire frequency or fire cycle, which is the average interval between fires at a site. Differences between the slopes of the regression lines calculated for each identified time period were tested for with Student's test (Davis, 1986).

**Results**

According to the graphical method outlined above the time period 1850-1985 was typified by fire frequencies of 55 years or less (Fig. 5 and Tab. 1). There were two short time periods with much lower frequencies. Fire frequencies were low between 1862 and 1881 (the last portion of the Little Ice Age) and during the mid 1950s through the 1970s. Historical fire records are available for WBNP between 1950 and 1990 and can be used to test the reliability of the estimates of short-term changes in fire frequency based on the cumulative stand age frequency
Table 1. WBNP temporally partitioned fire frequency estimates

<table>
<thead>
<tr>
<th>Time period</th>
<th>Fire frequency</th>
<th>n</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980 - 1985</td>
<td>26***</td>
<td>5</td>
<td>0.82</td>
</tr>
<tr>
<td>1956 - 1979</td>
<td>435***</td>
<td>5</td>
<td>0.88</td>
</tr>
<tr>
<td>1882 - 1954</td>
<td>55***</td>
<td>47</td>
<td>0.99</td>
</tr>
<tr>
<td>1862 - 1881</td>
<td>186***</td>
<td>4</td>
<td>0.89</td>
</tr>
<tr>
<td>1850 - 1859</td>
<td>38***</td>
<td>5</td>
<td>0.90</td>
</tr>
</tbody>
</table>

*** P < .002, two tailed test

method. The historical records indicate a fire frequency of 333 years between 1956 - 1979 and fire frequency of 29 years between 1980 - 1985. The cumulative stand age frequency method estimates (Tab. 1) compare fairly well with the fire frequencies estimated from historical records in terms of the magnitude of difference in fire frequencies for the two periods.

Discussion

The WBNP data set provide some evidence of linkage between fire frequency and temperature changes at the close of the Little Ice Age. However, interpretation of these data is problematic. The high fire frequency between 1882 and 1954 corresponds with post Little Ice Age climatic warming in the northern hemisphere and the western subarctic of Canada (Fig. 1). However, there is evidence for relatively high fire frequencies prior to 1862 that remains to be explained. The reduced fire frequency between 1956 and 1979 is consistent with a cooling phase evident in hemispheric and local climate records, while the increased fire frequency in the 1980's corresponds with increasing temperatures (Fig. 1).

While there is a general agreement between fire frequency and the mean annual temperature, it can be noted that the fire frequency between 1910 and 1935 was 8 times higher than it was between 1956 and 1979. This difference occurs despite the fact that the mean annual temperatures during these two times were essentially the same (Fig. 1). As precipitation amounts can greatly affect the availability of fuel for burning, this anomaly may be the result of precipitation patterns not being in phase with temperature variations.

While the fire frequency record from WBNP indicates five changes in fire frequency since 1850, similar studies from other sites in the Canadian Rockies and the boreal forest of Quebec have noted no changes during this period (Johnson et al., 1990; Johnson and Larsen, 1991) or only one change during this period (Masters, 1990; Bergeron 1991). The higher frequency of changes noted in this study are likely due to the shorter time span examined (approximately one-third the length of the other studies) and therefore the higher resolution of detail. Alternatively, the variation in fire frequency in WBNP could reflect regional differences in climate patterns. An additional difference between this study and those by Masters (1990) and Bergeron (1991) was that they found a one step decrease in fire frequency during the period 1850 to 1985 while we found alternating periods of shorter and longer fire frequency.

CONCLUSIONS

The results we present here illustrate several ways in which dendrochronological records may be used to examine the response of the boreal forest to recent climatic changes. Despite the preliminary nature of these results, they allow us to suggest several conclusions regarding climate warming and boreal forest response. Instrumental evidence of climatic warming
between approximately 1880 and the 1940s appears to coincide with marked changes in the radial growth rates and recruitment of *Picea* trees at the arctic and arctic-alpine treelines in western Canada. Fire frequencies in the central boreal forest also appear to have been high during this time. At the sites we have examined the present conditions of the boreal forest do not reflect constant rates of growth, recruitment and fire disturbance. The close relationship between post Little Ice Age temperature increases and past changes in growth rates and recruitment of *Picea* at the arctic and arctic-alpine treeline suggest that the response of treeline populations to future climate warming could be similarly rapid. However, the more ambiguous relationship between temperature increase and fire, coupled with the potential importance of precipitation in controlling fire frequency, make it more difficult to predict how this important agent of disturbance will be affected by future warming.

**REFERENCES CITED**


HOLMES, R.L. 1991. *Dendrochronology program library user’s manual*. Laboratory of Tree-Ring Research Research, University of Arizona, Tuscon, AZ.


JOHNSON, E.A. and VAN WAGNER, C.E. 1985. The theory and use of two fire history mod-...
patterns of tree growth at Churchill, Manitoba, Canada. *Arctic and Alpine Research* 20:199-211.


THE CANADIAN ARCTIC REALM AND GLOBAL CHANGE

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L5L 1C6

ABSTRACT
Since the great deglaciation, the boreal and arctic vegetation has been a subject of changes due to extrinsic (climate) as well as intrinsic (ecological) driving forces. Although much can be learned from the past palynological and paleobotanical record, newly emerging variables might strongly influence future responses of the boreal and tundra biomes. Simple extrapolations from the past into the future may not suffice. What are the new variables? How fast and great might such an adjustment be? Our predictions could be only as valid and correct as the analyses of the past and present variables involved.

Future research will be driven by two objectives:
1. prediction of climate trends and northern vegetation adjustment to provide guidance to society and government and to satisfy our curiosity, and
2. inventory and monitoring of selected tundra stands to establish a baseline for future reference (i.e. invaluable service to future science).

INTRODUCTION
In the global climatic framework, the circumpolar regions have played the role of a heat sink, absorbing excess energy generated in the lower, especially the tropical, latitudes. While the heat subsidy to the Eurasian northern regions is efficiently delivered, mainly by the ocean currents, the New-world Arctic is being supplied with much less energy via atmospheric heat transfer. The rare composite satellite photograph of the northern polar regions (Figure 1) shows clearly the effects of an uneven heat distribution within this circumpolar realm. On the picture, upper Scandinavia, the Siberian coast and Alaska encircling the Arctic Ocean show extensive areas of open waters and snow-free landscapes, while waters of the Canadian Arctic Archipelago are still "frozen" and the land is snow or ice covered. A photograph of the Antarctic continent (Figure 2) covered in its entirety with ice, shows no such regional anomaly. This observation alone gives an indication of the impact that global warming may have on regions of the northern hemisphere, particularly the Canadian North.

In Figure 1, the Canadian Arctic region (Yukon Territory excluded) resembles an "icy-island", a remnant, and, perhaps, heir apparent, of the past ice age. If the climate keeps its warming trend, this icy island should, in time, disappear and a prosperous era of a "green-land" will set its course. On the other hand, should the expected increase in winter precipitation (snow) prevail, the resulting vector of delayed snowmelt, frozen ground and increased duration of high albedo, might shift the direction of the climatic change towards neoglacialization. The Canadian Arctic seems to have a strong predisposition for re-enactment of the pleistocene scenario. The Little Ice Age rehearsal manifested by the advance of outlet glaciers and expansion of major ice sheets has been the most recent exam-

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ple of this readiness (Barry et al. 1975; Andrews et al., 1976). This attests to the notion that, in fact, the core regions of the Canadian Arctic are still in a state of a persisting, yet concealed, glaciation. Occurrence of a deep and cold permafrost, presence of permanent ice caps and late snowbanks, and often incomplete snowmelt of entire landscapes suggest unequivocally how marginal and frail the present climatic balance has been.

Figure 1. Circumpolar Arctic mosaic of satellite pictures 1989. Note that the Canadian Arctic and Greenland (lower centre) are ice or snow covered while the Eurasian Arctic, Alaska and Yukon are mostly snow free. By courtesy of CIRES, University of Colorado, Boulder CO.

Models of the climate change impact on northern ecosystems such as the General Circulation Models (GCM’s; Etkin and Agnew, 1991) suggest a significant warming trend, mainly in winter. These models predict a longer snow-free growing season, with more precipitation and the sea ice disappearance much earlier than at present. Some authors, however, argue that in a permafrost region more precipitation, especially if deposited as snow, will rather delay the snowmelt (Jefferies et al. 1992). The late start would disadvantage the vegetation since it would miss the period when the radiation is at its peak. Past the summer solstice the quality of the growing season diminishes since the organisms (green plants in particular) function against the descending slope of the decreasing solar radiation and ambient temperatures. The net effect would be a reduction, even a cancelling, of the underlying influence of the climate warming.

Figure 2. Antarctica 1986. By courtesy of CIRES, University of Colorado, Boulder, CO.

A pattern of delayed snowmelt and its effect on vegetation can already be seen, displayed on a large scale across the Canadian Arctic. The “icy island” is generally colder and drier than is the rest of the northern circumpolar regions, and remarkably resembles the extent of the vanishing continental ice sheet (cf. Figure 1). The annual snowmelt, which is earliest at the “island’s” margins, follows the pattern of the shrinking continental ice masses of the past.
The satellite photograph of the Canadian High Arctic (Figure 3) captured the region during a snowmelt period, July 3, 1978. It clearly shows that the north- and south-western islands are snow-free earlier (two to three weeks earlier) than are the central core and the eastern margins of the archipelago. The abundance and distribution of the vegetation complexes in the western and south-western part of the region (Figure 4) shows striking similarity with the early snowmelt pattern seen on the satellite picture. These plant communities experience a longer growing season which usually starts before the summer solar radiation peak, and allows them to fully complete their annual cycle.

Figure 3. A satellite photograph of the Canadian Arctic during the snowmelt period July 3, 1978. Note that the north- and the southwestern islands are snow free earlier than are the central core and the eastern margins of the archipelago.

Figure 4. Predominant vegetation complexes in the Canadian High Arctic. The lusher vegetation is distributed in the southwest regions of the map.

which are also snow free earlier (cf. Figure 3), and have longer growing season than the central and northeastern regions. After Bliss, 1977.

Figure 5. Map of East-central High Arctic for orientation to Figures 6 and 7.

Figure 6. Satellite photograph of East-central High Arctic (cf. Figure 5), taken July 7, 1977. Note that Devon, Cornwallis, Prince of Wales and Somerset Islands; Boothia and Brodeur Peninsulas, and the Lancaster Sound are free of snow or ice this early-summer year.

The extended length of the growing season, when compared with the east part of the region, has a cumulative impact on the vegetation establishment in these, for plant development, climatically marginal environments (Svoboda, 1986). Year to year weather fluctuation is often neglected when the climate warming scenario for northern latitudes is being considered. The next set of figures offers an insight into the seasonal variability in terms of snowmelt timing and resulting duration of the growing season in the Lancaster Sound region. (See Figure 5 for area orientation). Both satellite pictures (Figure
Figure 7. Satellite photograph of East-central High Arctic (cf. Figure 5), taken July 7, 1978. Note that the islands and peninsulas, including the sounds are still snow or ice covered this late-summer year.

6 and 7) were taken on the same day, July 7, but in two consecutive years 1977 and 1978. There is a striking difference in the duration of snow and sea ice between the two years. In 1977 the Lancaster Sound, Devon Island (except for the permanent ice caps), Somerset Island, Boothia and Brodeur Peninsulas were free of snow or ice, respectively, at least as early as July 7 (Figure 6). In 1978, on the other hand, the sounds were still frozen solid and also the islands were under the snow cover on the same date (Figure 7). Clearly, there was a minimum three week difference in the length of the growing season in the area between these two years. This extreme swinging of early and late, long and short, warm and cold arctic summers have been a common experience of arctic old-timers. The 1992 summer season which was late and cold, and the 1993 season which was early and warm, provide the latest evidence of the climate year-to-year erratic pattern.

The following observations can be made when the short- and long-term consequences of the climatic fluctuations are considered: 1. Measurable difference in vigour, productivity and reproductive success of tundra plants growing in the depicted region could be expected as a result of the two contrasting summers of 1977 and 1978, or 1992-1993; the warmer summers being more favorable for plant growth, the colder suppressive. 2. In case of a climatic warming, similarly, a longer series of warm summers, followed by a shorter series of cold summers might wipe out the gain and progress the vegetation has achieved over the preceding favorable period (Svoboda and Henry, 1987). The progress of plant advancement is slow and tardy, its reversal fast and deadly, as can be witnessed on many arctic islands showing scars (lichen kill zones; Andrews et al. 1977, Dyke 1977) and still devoid of higher plants due to the recently terminated Little Ice Age period. The impact on the secondary (herbivores) and tertiary (carnivores) consumers would be even more dramatic. In this "icy-island" territory of Canada, frequent past climatic anomalies ought to be considered one of the most crucial factors in maintaining the islands as polar deserts (Svoboda 1982, Svoboda and Henry, 1987). Only a very long-term and persistent shift towards the warmer climate might make a substantial difference for a high arctic vegetation expansion and its ecosystem development. Other adverse factors to be considered, are as follows.

PERMAFROST

Historical patterns of northern climatic regimes have expressed themselves in the regional distribution, depth and temperature of the permafrost (Brown, 1967). This, in turn, has influenced the vegetation cover, although it can also be implied that the thickness of permafrost and northern vegetation "thinness" share a common cause in the prevailing cold climate. The colder the permafrost, the more shallow the active layer in summer, and the stronger the potential adverse effect on vegetation (Edlund and Alt, 1989).

In terms of energy balance, the colder and deeper the permafrost, the greater the regional heat sink (Judge 1973, 1977). Canadian polar regions will for a long time, "drain" much of the imported "greenhouse" heat. Nonetheless with a prolonged period of warming the permafrost should get less cold, the active layer deepen and the present permafrost zones shift inevitably northwards (Maxwell, 1992). The process may take centuries (Lewkowicz, 1991).

In the meantime, cold soils with a shallow active layer could hinder root penetration and adversely affect root physiology (Haag 1974). Consequently, the cold permafrost may develop
an anomalous relationship with future warmer climate, and would continue to interfere with vegetation development. Hence, although the aboveground meso- and microclimate might become favorable to more growth, vegetation expansion would progress less vigorously than under conditions with no or a less cold permafrost.

Feedback mechanisms between permafrost and tundra vegetation development should also be considered. Warmer summers might initially bring about a deepening of the active layer. In areas with sufficient soil moisture this should release more nutrients from the previously frost-locked soil and promote more vigorous growth. However, the subsequent expansion of the vegetation cover would, in time, cause shading, which, in turn, might restrict the heat flux to the ground. As a result, the permafrost table may start raising again, hindering once again plant growth and causing a pull-back of more sensitive species. A cyclic-like succession, as observed in the forest-tundra transition (drunken forest; Sveinbjörnsson 1992) might follow for a considerable time until the permafrost system exhausts its potential as a heat sink which, under these conditions, might take a very long time.

On a global scale, the enormous heat absorbing capacity of the world permafrost regions, in tandem with increased Carbon fixation by terrestrial vegetation and marine organisms, the CO₂ absorbing capacity of oceans, enhanced evapotranspiration and cloud formation (Lovelock and Margulis, 1974; Maxwell, 1992), may participate in the autoregulatory processes of the Geo-Biosphere and thus assist in moderating the global greenhouse effect.

Boreal and subarctic peatlands (one third of which are in Canada) have been a weak carbon sink for millennia (Ovenden 1989). It can be assumed that after a temporary readjustment to new climatic conditions during which their overall carbon balance might become slightly negative (Jenkinson et al. 1991), peatlands will continue to be a carbon sink, possibly a more significant one than at present (Miller et al. 1983). It can also be expected that the present embryonic bogs of higher latitudes will expand into blanket bogs. In time these peatlands will spread over presently barren grounds shifting to much higher latitudes. This, indeed, will not happen without an effect on permafrost beneath. After becoming more protected by vegetation, permafrost table will rise, active layer will become shallow again, and the associated cold temperatures in the root zone will interfere with further plant establishment and advancement.

NUTRIENTS AND NITROGEN

From the sixteen or so biogenic elements utilized by terrestrial organisms, four are being supplied mainly by means of the atmosphere. These are Carbon, Hydrogen, Oxygen and Nitrogen. All other life supporting elements are derived from the mineral breakdown of the earth crust. While carbon dioxide (CO₂) and water (H₂O) are generally freely accessible to plants through leaves and root system, respectively, atmospheric Nitrogen has to undergo a chemical conversion to become available. This is an energy requiring process which certain lower plants and nodulated higher plants have evolved the ability to do. Once a sufficient stock of nitrogen is accumulated in natural ecosystem, nitrogen requirements are usually secured from decomposing tissues due to recycling. If there is a shortfall, it is supplemented by on-site N-fixation and "acid" precipitation. The supply of the other mineral elements also relies on recycling, their balance ultimately coming from weathering.

Various world ecosystems are to a different degree nutritionally limited either by nitrogen or by other mineral elements, forcing their living inhabitants to develop often sophisticated economic strategies for their sustainable maintenance. The Tundra Biome is no different from temperate and other southern systems in mineral nutrient and nitrogen requirements. It, however, varies greatly in three aspects. Since deglaciation only an incomparably low nutrient stock has accumulated in the standing crop for recycling (diminishing to virtually zero with increasing latitude). Decomposition processes are sluggish and restricted to a few weeks of the growing season. Finally, quite a large portion of
the accumulated biomass, still holding onto its nutrient stock, has been excluded from any recycling, because the lower peat strata have been locked in the permafrost. Resulting shortage of nutrients, in particular of the unstable nitrogen, puts arctic ecosystems in a special category also with respect to climate change.

Besides being chronically heat-energy limited, arctic ecosystems are perhaps even more nutrient limited. In permafrost regions soil nutrients can be obtained only from a thin portion of the earth crust, called active layer. Also nutrient concentrations are extremely low in these regions (except for Ca, and Mg in some soils; Walker and Peters, 1977) because of their repeated spring depletions and loss in run off after snowmelt. Places where natural manure was deposited, resting places of dead animals and plots where artificial fertilizer was applied (Henry et al. 1986) have demonstrated incred-

ible incremental plant growth under the same taxing climatic conditions. Consequently, an assumption seems to be justified that a high percentage of arctic plants have developed rich ectomycorrhizal associations (Bledsoe et al. 1990; Kohn and Stasovski, 1990) to expand their root nutrient absorbing capacity in a nutrient poor environment.

Nitrogen in available form is also present in very low concentrations. This element, however, is supplemented by being generated de novo every season in quantities able to support a minimum plant growth and a lean ecosystems sustenance.

Recent research of Bliss et al. (1990) and Chapin et al.(1991) on the ecosystem development of a coastal lowland on Devon Island, following postglacial uplift, showed the importance of blue-green algae (cyanobacteria) in nitrogen fixation and early stages of carbon

<table>
<thead>
<tr>
<th>Substrate (rating)</th>
<th>Dolomite</th>
<th>Sandstone</th>
<th>Shale</th>
<th>Mixed lithology</th>
<th>Granite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarseness</td>
<td>Solid bedrock</td>
<td>Boulders</td>
<td>Gravel</td>
<td>Coarse</td>
<td>Fine</td>
</tr>
<tr>
<td>Moisture</td>
<td>Dry</td>
<td>Dry-Mesic</td>
<td>Mesic</td>
<td>Wet-Mesic</td>
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<tr>
<td>Temperature</td>
<td>Cold</td>
<td></td>
<td></td>
<td></td>
<td>Warm</td>
</tr>
<tr>
<td>Exposure</td>
<td>Very windy abrasive</td>
<td>Windy</td>
<td>Less windy</td>
<td>Sheltered</td>
<td>Protected</td>
</tr>
<tr>
<td>Disturbance</td>
<td>Regular</td>
<td>Frequent</td>
<td>Occasional</td>
<td>Rare</td>
<td>Absent</td>
</tr>
<tr>
<td>Succession/Development Index</td>
<td>None or Retrogression ≤ 5</td>
<td>Standstill</td>
<td>Slow</td>
<td>Moderate</td>
<td>Fast</td>
</tr>
</tbody>
</table>
accumulation. Also, studies of Elster and Svoboda (unpublished) indicate that wet zones in front of a melting glacier and polar desert plateaus after snowmelt support vigorous algal growth, of which blue-greens are a significant component. In retrospect, this suggests that these organisms have pioneered arctic ecosystem development following the continental ice retreat. They still maintain a high capacity for nitrogen fixation (Stutz, 1977, Henry and Svoboda, 1986), supplying about 10% of total uptake in arctic ecosystems at present (Chapin and Bledsoe, 1992).

It can already be envisaged that a climatic change in favour of arctic ecosystems development in the future may be hampered by a low supply of the building materials for a biomass build-up. In a demand versus supply situation, the rate of supply becomes the controlling factor. In other words, vegetation expansion and biomass (peat/organic matter) build-up cannot progress faster than the rate of nitrogen fixation and mobilization of other essential elements will allow.

Proliferation of blue green algae (and consequently also Nitrogen fixation) is to a high degree a function of a free space, ready for use on wet yet barren polar landscapes. Future research will determine if the rate of nitrogen fixation would be able to keep pace with the expected increase of primary production and expansion of the vegetation cover or if it may dwindle. In the latter scenario the persisting nutrient shortage may act as a break, slowing down the potentially explosive vegetation expansion due to sudden climatic amelioration.

REGIONAL AND LOCAL THEATRES OF CHANGE

Very few places in the world display such staggering differences in microenvironmental conditions over short distances as can be typically observed in arctic tundra. Hence another set of variables to be considered when contemplating an arctic vegetation response to climate change. Table 1 attempts to illustrate how diverse conditions may result from an arrangement of favorable, less favorable and unfavorable variables at a single area or habitat. An arbitrarily selected set of environmental variables, arranged in gradients, might be used as a tool to compose a “successional/developmental index”. This would give an indication about the degree of a potential response of a stand of vegetation to climate amelioration in a particular locality. Unless all site variables are potentially supportive for vegetation advancement, the site response to a favorable climatic change will be less than optimal.

An organism, a plant in particular, does not recognize a climate, only microclimate. It does not occupy a landscape but a biotope where microclimate is a component of the local microenvironment. If the overall climatic conditions over the Arctic sufficiently improve, the future arctic landscapes are bound to be greener and their ecosystems more lush (Edlund, 1991). Successional process leading towards this new balance with the climate will have an appearance of a mosaic of spreading communities performing according to local conditions.

GLOBAL WARMING AND TERTIARY CLIMATE

In order to grasp the concept of the present global warming it helps to see this phenomenon in a historical perspective. Its extent could be as minor as was, for instance, the mild positive climatic aberration (~1°C warmer than normal) of the Little Climatic Optimum (LCO). This early medieval warm period which marked the end of the first and the beginning of the second millennium lasted only a few centuries. Yet, it has been associated with the Thule migration from Alaska (Barry et al. 1977) and it enabled the expansion of the Norsemen society in “Greenland” if not the island’s discovery. It is also known to have had a pronounced influence on medieval agricultural practices (Clairborne 1970, Ingram et al. 1981).

Conversely, the present global warming could be as significant as during the postglacial thermal maximum (~2–3°C warmer than normal) which lasted more than 4000 years and came to a climax some 7000 years ago. This was an era of high terrestrial productivity and of a treeline expansion much beyond its present occurrence in Canada (Nichols 1976, Ritchie, 1987). It is
possible that this climatic period of the distant, yet still postglacial, past might represent the closest approximation to the predicted modern climatic trends.

The extreme warming scenario could be contemplated as a result of a "run-away greenhouse effect". The human-triggered global change would swing far out of the range of climatic variations of the present interglacial epoch and restore a climate comparable to that of the Tertiary. In spite of such an alarming thought, this scenario is not so unrealistic considering that credible climate models predict for the High Arctic a 2.0 - 2.4 times temperature increase over and above the projected global warming of 3.5°C, should the atmospheric CO₂ double as it is expected in less than 50 years. This would translate into a more than 9°C temperature increase in winter and about 3°C increase in summer (Maxwell, 1992), a warming trend unsurpassed in postglacial times (Matthews, 1989).

It ought to be mentioned that the present "greenhouse warming" is a tropospheric phenomenon. In contrast, the predicted stratospheric temperature is estimated to become 5-10°C colder, pointing further to the terrestrial causes of the warming. No dramatic increase in solar emissions (Foukal 1990) or influence of other causes such as those described by the Milankowitch model (periodic changes in geometry of the earth's orbit, etc.; Gribbin, 1978) seem to be involved. For better or worse, this places the control over the present climate largely back into human hands.

Two decades ago a notion about the recurrence of a Tertiary climate would stir little commotion among climatologists and ecologists for such an idea would have been considered largely academic. What knowledge about the Arcto-Tertiary (nemoral) vegetation in the present arctic realm was confined to a small group of experts on northern paleobotany (Love and Love 1974).

As we learn more about the tertiary period and its vegetation, we begin to develop a feeling for this "earth normal" climate. We are astonished that the northern Ellesmere and Axel Heiberg Islands were forested by redwood and tamarack some 45-55 Million years ago (Basinger et al. 1989; Thurston et al. 1989). Even more, when we read that only 3 Million years ago floristically rich forests covered now mostly barren Banks (73°N) and Prince Patrick (77°N) Islands, and that forested-tundra existed on Meighen Island (80°N; Matthews, 1989) and on the northernmost tip of Greenland at Kap Kobenhavn (83°N) some unbelievable 2 Million years ago, during the Pliocene-Pleistocene transition (Funder et al 1985).

Only when the almost incomprehensible reality of the forested upper reaches of the Canadian archipelago sinks deeper into ones awareness, does a more complete image about the late Tertiary climatic scenery emerge. Several months-long winter darkness, yet absence of permafrost! Deep winter cooling due to otherwise inevitable long-wave heat loss during the long arctic night must have been countered by high cloud cover and further compensated by heat released by unfrozen ocean and imported by warm winds. Hence, the logical requirement for higher warming in winter as predicted by all climate change models.

CONCLUSIONS

The unprecedented rate of the ongoing global transformation concerns scientists and worries governments. Rapid climate fluctuations have been reported in the distant past: at the end of the last glaciation period temperatures in Greenland rose by 7°C in 50 years and rate of snow accumulation changed abruptly within a few years, as the recently extracted ice cores from the Greenland ice sheet have revealed (Dansgaard et al. 1989; Alley et al. 1993; Anonymous, 1993).

In spite of such a rapid, if not an "instant" climate switch, its full impact may, nevertheless, spread over decades and centuries. Also the global society is changing very fast and thus represents even greater unknown factor than is the climate.

For peoples of northern Canada the prospect of climate warming, should generally be an optimistic one. In an environment which has been stressful for plants animals and humans, the long-term climate amelioration
should herald better times marked with greater productivity, higher potential of renewable resources and economic prosperity. In the Arctic the year-to-year climate fluctuations have, so far, disallowed detection of any significant trend in any direction in the Arctic, although the possibility of an unexpected turn of events does exist.

There is a great interest among members of the scientific community to initiate thorough research programs in order to monitor any changes in structure and functioning of various world ecosystems. Although the micro-responses of organisms (phenology, physiology) to climate fluctuations are immediate and relatively easy to record (Chapin et al. 1992), the macro-responses (e.g. shifts in vegetation zonation) are long-term and hard to observe in a single human life span (Mathews, 1989).

The objective of one of such programs, the International Tundra Experiment (ITEX), launched in 1990, has been to establish permanent study sites in the circumpolar tundra regions for long-term observations. The program includes timing of phenological events in selected plant species (especially onset of flowering) and monitoring of growth and physiological responses related to seasonal weather patterns. These arctic plants were chosen as "non-meteorological integrators" and phytometers capable of a holistic response. In Canada several sites have been considered and some already established as part of CANTEX, which is the Canadian section of ITEX. It is advisable, if not imperative, that in Canada we begin earnestly monitoring permanent plots with tundra vegetation in a similar way as climatic data have been gathered for over a century and will continue to be recorded in perpetuity.

REFERENCES CITED


Svoboda, J. 1982. Due to the Little Ice Age climatic impact, most of the vegetative cover in the Canadian High Arctic is of a recent origin: a hypothesis. Proceedings of the 33th Alaska Science Conference/AAAS Arctic Division), p.206.


PLANT PHENOLOGY IN ALBERTA: A BIOMONITOR FOR CLIMATE CHANGE

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ABSTRACT

Phenology, the study of the seasonal timing of life cycle events, can be used effectively to track global warming. Temperature is the most important factor influencing spring plant pheno-
logy in temperate zones of the earth. In partic-
ular, flowering of woody species and perennial
herbs is in response to accumulated temperature. International phenological networks of
observers reporting on phenology have existed
for up to 2 centuries in Europe. The Alberta
Phenology Survey, launched in 1987, asks vol-
unteers to report on flowering times for 15 widely-
distributed “wildflowers”. A considerable
proportion of the survey’s 200 plus observers are
from northern Alberta. Recent phenological
data, when compared to historical Alberta
records, show a trend to earlier spring develop-
ment. This ongoing study provides a valuable
baseline against which to compare the pheno-
logical response to potential future climatic
warming in Alberta.

1 Elisabeth Beaubien is Coordinator of the Alberta Phenology Survey at the Devonian Botanic Garden. She is President of the Alberta Native Plant Council. Elisabeth has worked as an interpretive naturalist, environmental educator, and planned for federal parks across Canada. Her current interests include preservation and promotion of our indigenous flora.
CHANGES IN CLIMATIC VARIABILITY IN THE CANADIAN NORTH AND IMPLICATIONS FOR EXPANSION OF AGRICULTURE UNDER CONDITIONS OF GREENHOUSE WARMING

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ABSTRACT

This study concerns the investigation of how changes in climate variability could affect agricultural production. To date no systematic studies of this effect have been made, whereas changes in climate variability, in addition to changes in mean conditions, could have serious effects on crops. Currently there is very little certainty regarding how climate variability will change in a greenhouse-gas-warmed world. The first part of this presentation provides a review of recent findings regarding changes in interannual climatic variability with greenhouse-gas-induced warming. Particular focus is placed on the Canadian North where large increases in mean temperature are anticipated.

In view of the uncertainty regarding climate change, it is desirable to perform sensitivity analyses of how crop-climate models (e.g. the CERES-Wheat model) respond to changes in climate variability. We apply the winter wheat model to two climate stations in the wheat growing region of Kansas: Goodland in the western region, and Topeka in the eastern region. Although the area studied is relatively far from northern Canada, implications for the possibility of the expansion of agriculture into the North are drawn from this study in the Great Plains of the United States. Biome shift studies indicate that parts of what is now classified as boreal forest in Canada could become grassland and transitional grassland.

Time series of temperature and precipitation are simulated, systematically changing the interannual variance of the series (from 0.25 to 4 x the actual variance), and determining how the crop climate model responds to these changes. In addition, these variability changes are combined with mean changes of both temperature and precipitation. Results indicate that it is the relative magnitude of change of the mean and variance of the climate that determines their relative importance to changes in wheat yields. In general increases in variability of temperature and precipitation resulted in significant increases in yield variability and crop failures in the sensitivity experiments, but precipitation changes had a more pronounced effect. Decreased variability was not as helpful as increased variability was harmful to yields. Overall all experiments, the importance of considering not only mean but also variance changes of climate variables when investigating the effect of climate change on wheat yields is confirmed.

1 Linda Mears (Ph.D.) has published extensively on climate modelling, climate variability, and crop/climate interactions. She is a scientist at the National Centre for Atmospheric Research in Boulder, Colorado.
RESPONSE OF NORTHERN PEATLANDS TO CLIMATE CHANGE

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ABSTRACT
Peatlands cover 16% of Canada's land surface. They develop and are maintained in cool, moist areas of the world and are among the most climatically sensitive ecosystems. Peatlands are unusual in "greenhouse" scenarios because, on the one hand, they sequester the major "greenhouse" gas, CO₂, while on the other hand they emit large quantities of both CO₂ and the second most important "greenhouse" gas CO₄. Temporal changes in the rate of peat accumulation and in peatland distribution will have important consequences to the development of northern Alberta, where over 40% of the landscape is covered by peat. Our current research is to model wetland vegetation response to climate change using a model that integrates species response to climatic change in western Canada.

1 This paper is being published in the Journal of the Hattori Botanical Laboratory, Japan.
2 Dennis Gignac is an Assistant Professor of Biology at the Faculté Saint-Jean, University of Alberta. His research has focused on the effects of climate, physical, chemical and pollution gradients on the abundance and distribution of peatland bryophytes.
3 Dale Vitt is Professor of Botany at the University of Alberta and Director of the Devonian Botanic Garden. His current research interests include the taxonomy of bryophytes, biogeochemistry of peatlands, and reconstruction of peatlands in western Canada since the last glaciation. In 1992-93 he was awarded a Killiam Award Professorship.
WILDFIRE AS A FORCE IN GLOBAL CLIMATE CHANGE

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ABSTRACT

Forest fire is the most powerful annual summer event that changes the dynamics of the circumpolar boreal forest. Under predicted climate changes the fire season may be lengthened, wildfires may become more widespread and fire intensity and severity are expected to increase. These fires will provide a feedback loop to climate change by contributing greenhouse gases, primarily carbon dioxide, not only during burning but also during accelerated decomposition of organic material remaining after the fire.

These fires may have major effects on the vegetation of northern ecosystems especially at ecological boundaries or where ecosystems are already under stress. Our research has shown that changes from one vegetation type to another can occur after one fire event. For example, we have shown that weedy species can invade drought stressed plant communities that burned and we have also identified how trees at the arctic forest-tundra boundary can advance onto the tundra after burning.

INTRODUCTION

Residents of Canada and other northern circumpolar countries are concerned with the scenarios of climate change since Global Circulation Models predict that global warming over the next 30-50 years will be most evident in the northern regions (Bolin et al., 1986; Roots, 1989; Maxwell 1992). Climates in the north would be supportive of much more southern types of biotic systems (Emanuel et al., 1985).

Our goal is to convince you that fire may be the most important (widespread) driving force in changing the taiga under climatic warming conditions. At the time of burning, CO₂ is released to the atmosphere where this greenhouse gas will act as a feedback loop to global warming. In addition CO₂ release continues for one or more decades after the fire because of higher decomposition rates of organic matter, particularly in northern soils. As for climate change stresses on the biota of the ecosystem, it is our hypothesis that these energy and nutrient conservative ecosystems change very slowly even if the climate changes; however, fire can be a triggering event to remove species that are poorly adapted to the new climate regime. More importantly, fire modifies the physical environment and disrupts the population dynamics to such an extent that there can be strong changes in species abundance and new species may invade the burned area.

THE CIRCUMPOLAR TAIGA

More than ever before Canada is exploiting the boreal forest so Canadians, and most recently Albertans, are recognizing the extent and importance of this biological zone. The taiga in Canada and Alaska is about 373 x 10⁶ ha of the circumpolar total of 1214 x 10⁶ ha (Table 1). Russia has almost triple the amount of commer-

¹ Professor Ross Wein has studied the significance of forest fires in future climate change scenarios over the past few years. His geographic area of interest is the boreal and arctic regions of northwest Canada, particularly in and near Wood Buffalo National Park and in the Inuvik Region.

² Simon Landhäusser is a Ph.D. student working with Professor Wein on post-fire vegetation recovery and tree establishment in the Inuvik region.
Table 1. The extent (in $10^6$ ha and % of circumpolar total) of the boreal (taiga) zone in the circumpolar north (extracted from Kussela (1992)).

<table>
<thead>
<tr>
<th></th>
<th>Russia</th>
<th>Canada/</th>
<th>Norway/</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Alaska</td>
<td>Sweden/</td>
<td></td>
</tr>
<tr>
<td>Finland</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Partly forested</td>
<td>790 (65)</td>
<td>373 (31)</td>
<td>51 (4)</td>
<td>1214</td>
</tr>
<tr>
<td>Closed forest</td>
<td>673 (73)</td>
<td>203 (22)</td>
<td>44 (5)</td>
<td>920</td>
</tr>
<tr>
<td>Commercial forest</td>
<td>450 (71)</td>
<td>149 (23)</td>
<td>40 (6)</td>
<td>639</td>
</tr>
</tbody>
</table>

Table 2. Selected years with major regional fires in the circumpolar taiga.

<table>
<thead>
<tr>
<th>Year</th>
<th>Location</th>
<th>Total Area ($10^6$ ha)</th>
<th>Area Burned</th>
<th>Comments</th>
<th>Reference</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(10^6 ha)</td>
<td></td>
<td>Total %</td>
<td>(10^6 ha)</td>
</tr>
<tr>
<td>1987</td>
<td>Daxinganling, China</td>
<td>8</td>
<td>1.33</td>
<td>17 at least 4 major fires joined</td>
<td>Yun-Qian and Ji-Zhong (1989), Di and Ende (1990)</td>
</tr>
<tr>
<td>1989</td>
<td>northern Manitoba</td>
<td>36 (19)*</td>
<td>3.28</td>
<td>9 (17)* 60+ fires over 5,000 ha</td>
<td>Hirsch (1991)</td>
</tr>
</tbody>
</table>

* numbers in brackets represent greatest concentrations of multiple fires as estimated from maps.

Table 2. Selected years with major regional fires in the circumpolar taiga. Year Location Total Area ($10^6$ ha) Area Burned Comments Reference Total ($10^6$ ha) %1981 northern Alberta32 (11)*1.364 (12)*29 fires over 200 haDelisle and Hall (1987)1987 Daxinganling, China 81.3317 at least 4 major fires joined Yun-Qian and Ji-Zhong (1989), Di and Ende (1990)1989 northern Manitoba 36 (19)*3.28 (17)*60+ fires over 5,000 ha Hirsch (1991)* numbers in brackets represent greatest concentrations of multiple fires as estimated from maps. file: ros
cial forested land when compared to North America.

THE PRESENT IMPORTANCE OF WILDFIRE

Fire is the most widespread agent of unplanned change in the boreal zone (Wein and MacLean, 1983; and more recently, Johnson, 1992); fire rapidly modifies the carbon budget not only of the frequently dry upland forests but also of the forests with deep organic soils particularly after periodic severe droughts. This is not to negate other disturbances of disease or insects (there is an increased probability that fire may follow these disturbances as well) and especially harvesting, which covers millions of hectares annually, but periodically fire is the overriding force.

In the past decade there has been an unprecedented increase in the annual area burned by wildfires in Canada (Van Wagner, 1988; Figure 1). The 10 year running mean of annual area burned ranged from $1.5 \times 10^8$ ha in the 1930s and 1940s to $1.0 \times 10^6$ to the late 1970s. The years 1981 and 1982 were spectacular years with values of about 5.0 and $5.5 \times 10^6$ ha, respectively. These years were overshadowed by the burned area in 1989 of $7.39 \times 10^6$ ha, $3.28 \times 10^6$ ha of which was in northern Manitoba (Hirsch, 1991).

To add to the temporal pattern above it is instructive to understand the spatial dimension of past fires. During most years fires are scattered across the boreal zone of the circumpolar north, for example in the year 1980, fires were ignited across much of the western Canadian boreal forest. In other years there are concentrations of fires at the regional level (Table 2).

WILDFIRE SCENARIOS UNDER GLOBAL WARMING

Under $2 \times CO_2$ global warming scenarios it has been suggested that the aerial extent of fires may increase by almost 50%, the fire season may lengthen and the most severe portion of the fire season may shift to late summer (Street, 1989; Flannigan and Van Wagner, 1991). This increase of area burned has already occurred in the 1980s; does the future hold even more spectacu-
lar fire years? These unusually severe fires in the last decade could be useful in developing scenarios for future carbon budget dynamics under global warming (Kurz et al., 1992). In addition there is concern that carbon dioxide and other greenhouse gases released to the atmosphere during wildfire could increasingly strengthen the feedback loop to global warming if burned area and fire severity continue to increase.

CO$_2$ FEEDBACK LOOP TO GLOBAL WARMING

We have emphasized the importance of fire in the northern circumpolar forest but it has been estimated that global vegetation burning and forest conversion to agriculture releases 4 to $6 \times 10^{12}$ kg of carbon to the atmospheric annually; of this, the circumpolar countries contribute 1.2 - 1.8% and Canada contributes 0.50 - 0.75% (Crutzen and Andreae, 1990). Stocks (1991) provided more detailed estimates of carbon release for the circumpolar boreal forests over the past decade. He estimated the burned area at $5.6 \times 10^6$ ha with Canada contributing $3.0 \times 10^6$ ha. If $25 \times 10^3$ kg/ha is an average level of fuel consumption and if 50% by weight of this fuel is carbon, then the carbon release was $7.0 \times 10^{10}$ kg for the circumpolar countries and $3.8 \times 10^{10}$ kg for Canada.

These average values are valuable but it must be emphasized that burns far exceed these averages in some years and there are many other factors not included in these calculations. There is much variability of fire intensity from hour to hour and there may be large unburned or lightly burned patches within burned areas (Eberhart and Woodard, 1987). Deep burning fires under exceptionally dry years in forests with thick soil surface organic matter layers and in peatlands are not included. Multiple burning of areas is also not considered; during the first fire trees are killed but not consumed but in a second fire the dry trees would be oxidized to release considerable carbon dioxide. In addition, the accelerated postfire rate of carbon release by decomposition can contribute as much carbon to the atmosphere as during the fire. A.N.D. Auclair (personal communication)
conducted a simulation experiment and concluded that emissions during and after biomass burning may have been a significant feedback loop to global warming in the past 10-15 years. Release from tropical deforestation is very rapid and has been emphasized in the literature but northern ecosystems continue to release CO₂ for one to two decades after the fire because of accelerated decomposition under warmer soil conditions.

In calculating global carbon budgets the scaling problems become even greater. Fire is a major force in the Eurasian boreal forest (Stocks 1991) yet, until recently, few data have been available on carbon release rates from those vegetation types which tend to burn with surface fires rather than high intensity crown fires as in North America; even the spatial and temporal nature of burned areas were not readily available.

VEGETATION RESPONSES

Many predictions of biotic changes under climate change have and will be raised for discussion and testing but we will address only vegetation responses. Vegetation types especially in nutrient-limited and energy-limited northern ecosystems are conservative and show little change over time. Even under gradually increasing air temperatures the responses could be subtle. Slightly increased growth and reproductive capacity would be recognized as early changes. The response of vegetation types could be much more dramatic following fire. Fire not only removes part of the vegetation but also changes the energy and nutrient budgets dramatically. Changes in species abundances and even species numbers will be highly probable. Our research group has explored several case studies that illustrate these points.

We have examined an analogue of climate change in northern marshes by modifying moisture regimes (and indirectly soil temperature) of the vegetation. We moved soil-vegetation blocks upslope to higher elevations where flooding was less frequent (Hogenbirk and Wein, 1991). Little change in species abundance occurred over a two year period even though drought stress occurred. By adding the stress of fire there was a strong shift to opportunistic Eurasian weedy species (Tanacetum vulgare L., Sonchus arvensis L., Cirsium arvense (L.) Scop., Chenopodium album L.) especially under warmer soil conditions (Hogenbirk and Wein, 1992).

A somewhat similar example of the impact of severe fire at the arctic forest-tundra boundary has been studied recently by our team. It is well established that this ecotone is strongly controlled by climate; tree advance and retreat has occurred periodically over centuries and millennia as climate changed. Over the short term of two to five decades tree establishment in the tundra is minor; however, after a 1968 deep-burning fire near Inuvik, Northwest Territories and a subsequent climatic warming trend, Populus balsamifera, and Betula papyrifera moved well beyond their prefire locations (Landhäusser and Wein, 1993). In addition, Olsen (1993) has determined experimentally that the post-fire tree establishment success was not strongly influenced by changed moisture regimes (+30%, normal, ~30%) and/or changed temperature regimes (+3°C, normal); the main overriding force in increasing tree seedling establishment success and growth was increased fire severity (deeper burning).

The above studies consider only one fire but under climate change scenarios an increased probability of fire may lead to several fires in less time than normal. Multiple fires will lead to rapid and stepwise rates of change, replacing species that are poorly adapted with new combinations of species that flourish under the new environmental conditions. Plant species that disseminate propagules over wide areas, have high light requirements, have rapid growth rates and reach maturity quickly will be most successful in moving northward.

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REFERENCES CITED


ARCTIC INSECTS AND GLOBAL CHANGE

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ABSTRACT

The Canadian Arctic is strategically located for studies on the possible effects of climatic warming on the insect fauna. Although relatively simple compared to temperature or tropical ecosystems, the insect diversity is great enough and ecosystems are complex enough to provide useful insights into global climatic change. Furthermore, available models of climatic warming indicate that increased global temperatures are likely to occur first and to the greatest degree in the Arctic. Since insects have high reproductive and dispersal capabilities, short generation times, small size, and survive close to the limits for life, they are apt to respond faster to environmental change than any other group of organisms, such as plants or vertebrates.

About 2000 species of terrestrial arthropods have been reported from the North American Arctic, and probably about the same number of additional species are yet to be recognized or discovered. Since seasonality is a key feature of arctic environments, a particular emphasis is being placed on the study of finely-tuned adaptations of cold tolerance and control of life cycles which govern winter survival and phenology (e.g. insects-host plant relationships), thus enabling insects to cope with changing arctic conditions. In addition to their relevance to cryobiology, physiology and ecology in general, these adaptations give insights into the major constraint that governs arctic communities – the narrow seasonal window of productivity.

The Canadian arctic is one of the key regions in our country for studies of global change, because northern species and northern adaptations are most conspicuous there and faunal composition, ecosystem function, and adaptations to adversity are likely to be especially instructive. The arctic ecosystem is likely to provide particularly useful information on global warming because current theories estimate that it will experience significantly larger increases in temperature than temperate regions, and that warming will occur there first. In a recent State of the Environment Report (Environment Canada, July, 1992), the three arctic districts of Canada have shown gradual climate change over the last 100 years: the Mackenzie District has warmed substantially by an average annual temperature of 1.7°C (the greatest in the country), the Arctic Tundra District has warmed by 0.7°C, whereas the Arctic Mountains and Fiords District has actually cooled by an average of 0.6°C (the records here span only 45 years).

About 2000 species of terrestrial arthropods have been reported from the North American Arctic, and probably about the same number of additional species have yet to be recognized or discovered. Since insects have high reproductive and dispersal capabilities, short general times, small size and survive close to the limits for life, they are apt to respond faster to environmental change than any other group of organisms, such as plants or vertebrates. Since seasonality is a key feature of arctic environments, a particular emphasis of my work is being placed on the study of the finely-tuned adaptations of cold tolerance and control of life cycles which govern winter survival and phenology (e.g. insect-host plant relationships), thus enabling insects to cope with changing arctic

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1 Richard Ring is a Professor of Biology at the University of Victoria. He has served as President of the Entomological Society of B.C. in 1972 and 1984, and as President of the Entomological Society of Canada in 1992. His principal work deals with the cold tolerance of arctic insects. Recent interest in the Canadian Global Change Program has directed his studies toward the use of arctic insects in monitoring climatic warming.
conditions. In addition to their relevance to cryobiology, physiology, and ecology in general, these adaptations give insights into the major constraint that governs arctic communities — the narrow seasonal window of productivity.

Over the last three years several arctic-related projects have come to fruition. A survey of the aphids of the Western Arctic has identified 32 species of aphids on 23 different species of host plants. Several of these are new species of aphids for Canada and many others are range extensions. The collection area in the vicinity of the MacKenzie Delta is unique in North America and of great importance to biogeography since it forms a W-E transition zone between Beringian and "Hudsonian" faunal elements as well as a N-S transition zone between low arctic tundra and the northern boreal forest. Thus these aphids from the N.W.T. have added interesting information (especially the Beringian elements) to the aphid section of an up-coming book on the Insects of the Yukon published by the Biological Survey of Canada. The life cycle strategies of arctic aphids also hold the key to our understanding of the evolution of aphid life cycles (Dixon, 1991). Cavariella, whose species in temperate regions host alternate, has an arctic species (Cavariella borealis) which does not host alternate. This is due to the shortness of the arctic growing season which does not allow sufficient time for aphids to compensate for the huge losses incurred in moving from a woody primary to an herbaceous secondary host and back again, as well as to the fact that the potential secondary hosts, Umbelliferae, are relatively rare within the distribution of C. borealis. The production of winged forms is very costly in terms of rate of increase, and several authors have commented on the rarity of winged forms in species of aphids living in the arctic (Dixon, 1991). Particularly interesting in this respect is Euceraphis betulae which lives on dwarf birth (Betula glandulosa) in the vicinity of Tuktoyaktuk, N.W.T. Unlike all other species in this genus it has wingless virginals. Laboratory studies of cold hardiness show that arctic aphids have very similar over-wintering profiles to temperate species (O'Doherty and Ring, 1987). Adult Aphis epilobii collected in summer from the Western Arctic also possessed considerable supercooling capacity. The data are comparable with those gathered in other aphid cold hardiness studies and suggest that a general pattern of supercooling potential may exist in aphid species and may be independent of geographical or habitat origins.

Another possible insect/plant relationship that could be studied within the context of global change is that between willow gall-formers and their parasitoid complexes. For instance, our studies have shown that Pontania sp. (undescribed), a sawfly which forms leaf galls specifically on S. alaxensis in the low arctic tundra, has 7 species of ectoparasitoids and 2 species of endoparasitoids. All of them have been identified. Amavronematus amentorum, by contrast, is a sawfly that feeds on the aments of 9 different willow species in the Western Arctic. It also has a complex of 7 species of ectoparasitoids but only 1 endoparasitoid. These two nematine sawflies were the subject of an elegant comparative study. Pontania sp. feeds only on S. alaxensis; A. amentorum feeds on 9 different species of willows with different distribution and phenologies. Pontania sp. leaf galls overwinter under snow cover; A. amentorum overwinter in aments that are frequently exposed to ambient air temperatures. And both species have similar parasitoid complexes but with different species compositions. In summary results of a laboratory study of the overwintering biology of the sawflies and selected parasitoids are as follows. (1) Overwintering prepupae are freezing-tolerant. The overwintering response to low temperatures of the arctic species is similar to that of temperate zone sawflies, freezing being initiated at high sub-zero temperatures, near -10°C. (2) Freezing of sawfly prepupae is initiated by ice nucleators associated with the posterior hind gut wall, not by the contents of the hind gut as has been supposed in the past. Preliminary experiments suggest a proteinaceous structure for the ice nucleator. (3) Heterogeneity of overwintering habitats with respect to temperature is not a determinant of the overwintering success of these arctic sawflies. Differential survival following exposure to extreme low temperatures (-50°C) was
not evident between species overwintering in exposed and protected habitats. (4) Desiccation resistance, however, is an important component of winter survival. Both the rate of water loss under desiccative stress and the degree of total body water loss tolerated were correlated with the degree of exposure in their overwintering habitats. (5) Ensured freezing of nematine prepupae at high sub-zero temperatures can be considered adaptive since this overwintering strategy serves to reduce potential water loss during overwintering.

Divergent overwintering mechanisms were evident in the sawfly parasitoids studied. Significant features of the overwintering biology of the sawfly endoparasitoids and a novel overwintering strategy are enumerated for *Pontania* sp. (1) Endoparasitoid larvae, like their sawfly hosts, are freezing-tolerant. Outside their hosts, however, larvae of *Syndipnus* and *Ichneutes* can supercool extensively. Their extreme low temperature tolerance is similar to that of their hosts. (2) Freezing of immature, feeding endoparasitoid larvae occurs at the freezing point of the host prepupae and results from inoculation of the endoparasitoid's fluid compartments by ice crystals growing in the host hemolymph. Peculiarities in the structure of the endoparasitoid larval gut (i.e. lack of a functional connection between the mid- and hindgut) suggest the occurrence of nucleation across the gut wall. Overwintering strategies adopted by the ectoparasitoids were variable, with both freezing-tolerant and freezing-intolerant species present. All species, however, were found to be extremely desiccation resistant. *Scambus vesicarius*, the pteromalids and Bracman sp. were freezing-intolerant. The supercooling capacity of these species, while extensive, was insufficient to ensure survival in the absence of an insulating snow cover. *Adelognathus* sp. 1 exhibited a novel overwintering strategy. During early winter it also supercooled extensively. Later in the season, the freezing-point of this species was elevated significantly. The functional significance of the elevation is unknown. Like the nematine sawflies, *Adelognathus* is freezing-tolerant and is capable of surviving temperature extremes of at least -40°C. Resistance to desic-
cation and tolerance of water loss during winter differed between sawfly species. The differences appear to be correlated with the severity of conditions within their overwintering habitats. Sawflies overwintering in exposed habitats were more resistant to desiccation and more tolerant of water loss than those overwintering beneath the snow cover. Overwintering temperatures below the freezing points of the sawfly prepupae were demonstrated to reduce water loss over time in each species. Endoparasitoids were more resistant to desiccative water loss that were the nematine sawfly hosts, while ectoparasitoids were, in turn, more resistant to desiccation than endoparasitoids.

The results of this study point to a close correlation between micro-habitat conditions and the ability to resist desiccation as well as to tolerate the extreme cold of an arctic winter. Indeed, it is my contention that the synthesis of glycerol and perhaps other "cryoprotective" agents, play just as important a role in the prevention of desiccation during an arctic winter which induces dehydration by sublimation in an exposed, frozen insect. Adding weight to this hypothesis are the results of a study in my laboratory on the cold tolerance and desiccation resistance in the diapausing stages of the winter moth (*Operophtera brumata*) and Bruce spanworm (*O. bruceata*). These two species are unusual amongst insects in that they enter diapause during two different stages in their life cycle — an overwintering egg diapause and an aestival pupal diapause. The overwintering diapause eggs of both species are freezing intolerant, but have the ability to depress their supercooling points to somewhere within the range of -31°C to -39°C — temperatures far below those that would be encountered under natural conditions. Glycerol and galactose (a novel cryoprotectant for insects) accumulate during low temperature exposure to levels equivalent to 1.2% of fresh body weight. Similarly, the aestivating diapause pupae of both species supercool considerably (down to -16°C to -19°C) and they too are classified as freezing intolerant. However, this can be ascribed to the innate physio-chemical condition of the pupae, and has nothing to do with cold tolerance *per
The most interesting observation is that summer pupae also accumulate glycerol and galactose, as well as small amounts of glucose and an as yet unidentified compound. Total amounts of these so-called "cryoprotectants" reach 1.52% of fresh weight in winter moth pupae and 0.82% in Bruce spanworm pupae. Since aestivating pupae spend the summer within the top 1-2 cm of soil where temperatures can rise into the 30-35°C range, it is hypothesized that sugars and polyols play a protective role in preventing desiccation of pupal tissues during the extended (up to 5 months) summer diapause of these species. This is consistent with my current hypothesis that the synthesis of glycerol and other "cryoprotectants" may play a more important role in the protection of the insect against desiccation, especially during a severe arctic winter. This will entail testing the hypothesis with new species as well as reviewing the literature and my own published data to determine any possible connections between the degree of exposure of the overwintering microhabitat, desiccation resistance and cold tolerance in different taxa.

Finally, a long-term study has been initiated to examine the distribution, phenology and trophic patterns of insects in two vegetation community types at Alexandra Fiord, Ellesmere Island. Although the results are preliminary, progress to date is worth reporting since this study is unique in the Canadian High Arctic, i.e. examined differences in community structure of insects associated with a dry hummocky tundra site and a wet, sedge meadows site. Insects were collected using Malaise traps at Alexandra Fiord (20,458 specimens in all) were sorted to family with the exception of Cyclorrhaphan flies which were classified to sub-order, and mosquitoes which were identified to species and sex. Four families were unique to one or other of the collection sites: Aphididae (n=1), Calliphoridae (n=1), Ceratopogonidae (n=200), and Eulophidae (n=1). Ten families of insects were found to be significantly different in total number (all collection dates for the summer combined), four of which were highly abundant, showing obvious population trends over the collection period: Chironomidae, Culicidae, Ichneumonidae and Empididae. Phenological patterns were found to differ between collection sites at the family, species, and sex (of mosquitoes) levels. Despite our lack of detailed biological knowledge, groups were assigned to trophic levels based on extrapolation from information on habits in temperate and tropical ecosystems. As is the trend in polar ecosystems, diversity in trophic composition was very much reduced when compared with temperate and tropical areas. The notable absence of herbivory in adults suggests that the energy returns from this strategy may not be sufficient in so severe a climate. Differences between the two sites with respect to adult feeding guilds were low. Flower-feeding individuals were dominant in the sedge meadows community, although the actual abundance of flowers there is less than in the dry site, indicating that nectar may not be a limiting resource in the High Arctic.

Within the framework of a survey of insect communities at selected arctic sites, I plan to pursue my on-going investigation of overwintering strategies and cold tolerance of key insect species. Low temperature adaptations during summer activity and adaptations for overwintering will be investigated. During the summer season, growth and development of arctic insects are limited by temperature. Since numerous species exist just above their developmental threshold, even slight increases in environmental temperature are expected to result in range extensions of some arctic insects. In order to simulate such increases in temperature (a 2-4°C increase has been obtained in the artificial enclosures used by the British "Arctic Ecology" group), I plan to construct a series of insect-enclosure cloches similar to those used by the U.K. team. These are, essentially, a tent constructed of vertical, clear perspex walls, about 25 cm high, with the top covered with gauze through which rainwater can penetrate. A micro-climatic station plus data-logger will be necessary to monitor climatic differences within the cloche compared to outside. The woolly-bear caterpillar (Gynaephora groenlandica), one of the most freezing tolerant insects ever studied, would be an ideal subject for this experiment, since it feeds almost exclusively on arctic willow (Salix arctica) at Alexandra Fiord.
(Kevin and Kukal, 1993). In the low western arctic at Tuk, the birch aphid \textit{(Euceraphis betulae)} on dwarf birch would be the insect/host plant of choice. Other candidate species would include (1) the willow gall-formers and catkin feeders \textit{(Pontania} spp. and \textit{Amauronematrus amento- rum}, respectively) and their parasitoid complexes which have been studied extensively over the last 15 years in the low western arctic tundra, and (2) some insects which have been expanding ranges in the arctic, such as the red turnip beetle, \textit{Ennomoscelis americana}, and the western white butterfly, \textit{Pieris occidentalis}, that feed on mustard species (Cruciferae) which colonize disturbed areas, and which are extending their distribution in the western arctic.

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**REFERENCES CITED**


Danks, H.V. 1992. Arctic insects as indicators of environmental change. Arctic 45:159-166.


INFLUENCES OF CLIMATE ON ARCTIC MIGRATORY BIRDS

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ABSTRACT
Migratory birds are influenced by climate throughout their annual cycles. They are also exposed to other important extrinsic factors, which in turn are affected by climate; these include distribution of habitat density and behaviour of predators, and food supply. A simple graphic model expressing the interactions among the major factors influencing northern bird populations is used to describe the relationships that need to be understood in order to predict the likely responses of bird populations to global warming. A thorough understanding of the roles played by birds within the ecosystems they inhabit throughout the annual cycle will be necessary to predict the effects upon them of global warming and its associated ramifications.

INTRODUCTION
Our ability to assess possible impacts of climate change on wildlife is constrained by our limited knowledge of the effects of climate on wildlife (Diamond, 1990). Relationships between weather variables and wildlife responses abound in the literature (Whyte and Ignatiuk, 1989), but there have been few attempts to integrate this piecemeal information to describe general relationships between climate and wildlife (e.g. Root, 1988a,b).

Migratory birds that breed in the Arctic are instructive examples to illustrate the range of interactions involved in understanding such relationships, because their annual migratory cycle may take them between high arctic and antarctic environments and many of those in between. At each stage of the cycle they may be affected by climate, and may interact with other components of the environment that may themselves be affected by climate.

In this paper, we briefly review the better-known impacts of climate on various aspects of the annual cycle in migratory birds, to demonstrate the range of weather variables that must be considered to assess adequately the possible effects of a changing climate.

A general model of the major interactions between migratory birds and climate is given in Figure 1. This shows breeding, wintering and 'staging' areas (i.e. those used for extended periods during migration), each of which is influenced by climate. Most habitats in the wintering and staging areas have been affected by human land-use, which in turn is greatly influenced by economic, social and political behaviour. Since birds are subject to interactions (such as predation and competition) with other animals (including people), the populations and behaviour of these other species are of course also subject to climate, and can not be ignored.

1 Hugh Boyd worked on waterfowl research and management in the United Kingdom 1949-1967 and for the Canadian Wildlife Service 1967-1991. His present research includes two projects with international teams, studying the influence of weather on migrations of arctic-nesting birds, and their sensitivity to climate variations in breeding and wintering areas.

2 Tony Diamond graduated in zoology and ecology at Cambridge and Aberdeen Universities, U.K. He studied bird ecology, mainly in the tropics, from 1967 until joining the Canadian Wildlife Service (CWS) in 1983. Dr. Diamond now manages CWS' ecological research program in the prairies and Northwest Territories, and chairs the CWS Climate Change Working Group.
several major changes in arctic habitats are predicted by most models, including reduction in sea ice, rise in sea level, and thawing of permafrost (Tegart et al., 1990). Many sea birds [e.g. Thick-billed Murre (Uria lomvia), Dovekie (Plautus alle)] are dependent on the marine ice-edge at one stage or another of their cycle (Bradstreet and Cross, 1982), so reductions in many populations — or, at the least, significant changes in distribution — are very likely.

Sea level rise will inundate coastal habitats important for breeding or feeding to several species of geese and many shorebirds; net effects on populations will depend, in part, on the relative pace of inundation of former habitats and formation of new ones behind the rising shoreline. Goose habitat is determined largely by surficial geology (R.T. Alisauskas, unpub.), which will not change with rising sea-level and will limit the extent to which drowned habitat can be replaced naturally. It seems to be controversial whether thawing of permafrost will cause tundra to be wetter or drier (Tegart et al., 1990); a change in either direction may well induce changes in nesting distribution of many arctic birds through its impacts on the distribution of vegetation.

An important consequence of changes in distribution of ecoclimatic regions will be that species may come into contact with other species from which they are currently separated geographically; biotic communities are not fixed associations, but shifting assemblages of species brought together by a common tolerance for fortuitous or ephemeral combinations of environmental conditions (Pease et al., 1989).

Habitat distributions may also change for reasons other than climate, particularly land-use patterns imposed by people. Wintering arctic-nesting geese formerly lived and fed chiefly in natural wetlands, especially coastal marshes, in the U.S.A. As new forms of agriculture were developed inland, and some of these wetlands were damaged or destroyed by human ‘development’, snow geese in particular changed their behaviour to feed largely inland, especially on rice fields in southern Texas and Louisiana, rather than in the marshes (Bateman et al., 1988). Unlike many more specialized marshland birds, geese were able to exploit the transformation of farming by the more or less simultaneous introduction of large machinery for cultivation and harvesting, varieties of grasses, cereals and corn that can be sown early and give high yields, and the heavy use of artificial fertilizers (Nelson and Bartonek, 1990). In addition, the construction of artificial impoundments containing warmed water (e.g. effluents from power stations) encouraged geese to winter further north by providing them with safe winter roosts. From the 1930s to the 1960s, the development of the U.S. federal and state waterfowl refuge system undoubtedly helped geese to recover from the effects of intensive hunting in the late 19th and early 20th centuries (Nelson and Bartonek, 1990), though goose populations have now to some extent outgrown the refuge system (H. Boyd, unpubl.).

Farming is a major influence on bird populations (O’Connor and Shrub, 1986) and is greatly influenced by climate — determining what may be grown where — and by weather — determining yields and profits. Climate change may well have significant effects on agriculture, inevitably also affecting geese. Yet the pattern of agriculture, as the history of this century shows, is also greatly influenced by the terms of world trade and agricultural subsidies even in the absence of significant changes in global climate.

Changes in distribution of species

A recent analysis of winter distribution patterns of North American birds (Root, 1988a,b) suggests that, while habitat remains the most powerful predictor of species’ distributions, both range boundaries and abundance patterns are significantly shaped by temperature. Winter range boundaries of many species of songbird coincide with January isotherms, suggesting that the energy needed to compensate for the cold environment should not exceed about 2.5 times the basic metabolic rate (BMR). High-density populations in winter occur where energy demand does not exceed about 2.1 times BMR. These general relationships, within constraints imposed by habitat distribution, would allow the winter range of a species in a changed climate to
be predicted directly from January isotherm maps produced by a climate model.

Equivalent relationships between climate and distribution presumably exist in summer as well, but there are very limited databases from the Arctic from which such relationships could be developed. At present, the distribution of suitable habitat appears to determine the distribution of arctic-nesting birds more than does climate per se. Alternative approaches that are only beginning to be explored for arctic birds (Myers and Pitelka, 1979; Piersma and Morrison, in prep.; Wiersma and Piersma, in prep.) include the 'energy theory' of species distributions developed by Brown (1981) and Wright (1983), which relates the abundance and distribution of species to available solar energy (Turner et al., 1988). This theory, and Root's (op. cit.) results, suggest that climatic changes affect the distribution of species directly, in addition to changes mediated through changes in distribution of habitat.

Migration routes

The habitat requirements of birds on migration may be just as specific as those for breeding and wintering. A rise in sea level (if not countered by remedial construction, as in the Netherlands) is likely to inundate coastal staging grounds which are essential for shorebirds and geese migrating between arctic breeding grounds and southern winter quarters. In contrast, the rapid emergence of land on the shores of Hudson Bay (as a result of isostatic rebound after the end of the last glaciation – Peltier, 1990) causes changes in feeding conditions in the intertidal zone but increases in breeding habitat. Most populations are monitored routinely on the major staging grounds, so population changes resulting from these trends should be detected almost immediately.

Inland, habitat needs for shorebirds are less well-known (Harrington and Morrison, 1979). If a general drying trend occurs in the Canadian prairies and the Great Plains, as most models predict (Tegart et al., 1990), staging habitats will decline in quantity, and probably in quality. Increased water temperatures and salinity in the remaining prairie wetlands could well lead to increased frequency and severity of disease outbreaks, especially of botulism and avian cholera (G.A. Wobeser, pers. comm.), with potentially important impacts on geese, ducks and shorebirds.

Arctic-nesting geese are affected by agricultural practices in their spring staging areas in the prairie provinces and the northern U.S. Snow geese moving north lay down fat stores for breeding by feeding on corn and grain residues in the Canadian prairies; harvesting weather in the previous fall can affect the amount of food left in the fields over winter, to be exploited by northward-migrating geese next spring (Alisauskas and Ankney, 1992). Davies and Cooke (1983) suggested that soil moisture conditions in spring may have influenced the spring carbohydrate nutrition and fat storage of snow geese, by affecting the start and the speed of new plant growth. Alisauskas and Ankney (1992) found that snow geese in farmed staging areas in spring fed largely on waste corn from the previous fall, not on green plants. New growth is likely to remain important in staging areas north of intensively-farmed land and in breeding areas.

DIRECT EFFECTS OF CLIMATE

Timing of breeding

In many arctic birds, breeding is initiated at or shortly after snow-melt; late melt delays breeding and often lowers breeding productivity as well, either for energetic reasons [e.g. Atlantic Brant (Branta bernicla hrota) (Barry, 1962), Lesser Snow Geese (Anser caerulescens) (Davies and Cooke, 1983), Ross' Goose (A. rossi) (Ryder, 1967)], or through increased predation (e.g. Byrkjedal, 1980). In extreme cases, a late spring may encourage geese to move to entirely new breeding areas (McCormick, 1988), or lead them to abandon attempts to breed that year. For long-lived birds such as geese, it is important for adults not to endanger their own survival by nesting so late that they might be unable to complete regrowth of flight feathers before the onset of winter.

Some snow cover at the time of arrival can also be beneficial to some species such as
In the case of arctic-nesting geese, however, there are well-documented cases of the impact of extreme winter cold. In the southern United States, cold spells reduce the availability of green vegetation in ploughed and stubble fields and drive wintering snow geese into pasture, fallow fields or their ancestral habitat, coastal marshes (Alisauskas et al., 1988). More dramatically, in the very hard winter of 1976-77, two-thirds of the 125,000 brant (Branta bernicla hrota) wintering on the U.S. Atlantic coast starved and froze to death (Rogers, 1979). Yet the most important outcome of the disaster was a positive one for the survivors. Driven from their normal feeding on Zostera and other algae in the intertidal zone by the freezing of the foreshore, they moved inland to short grasses on airfields, golf courses and suburban lawns. Their descendants now turn regularly to short inland grasslands in late winter, when foreshore foods are depleted. There are other examples in Europe of lasting changes in distribution resulting from movements forced by exceptionally hard weather. For example, in the cold winter of 1978-79 about 5000 Canada geese, from the Swedish breeding population, visited northern Germany for the first time. This has led to the establishment of a wintering tradition, with 3-4000 remaining in Germany each year (Prokosch, 1991).

RELEVANT OUTPUT FROM CLIMATE MODELS

Measures currently available (e.g. monthly temperature means, precipitation totals) are of limited value. Temperature maxima and minima, frost-free and degree-days, and estimates of precipitation on finer geographic and temporal scales, are needed to predict effects of climate change on migratory birds and other wildlife. Estimates of snow-depth and dates of snow-melt will be particularly important, as will sea-surface temperatures and measures of sea-ice cover.

The current state of knowledge of climate/wildlife interactions is fragmented and poorly organized; it is not yet a coherent field of research. Currently we can estimate general sensitivities of wildlife to climate change, in the very broad fashion outlined here, but we have very limited knowledge of the sensitivities of particular species. This field of study barely exists as a discipline; if the serious challenges posed by climate change to arctic wildlife – and to their ecosystems in general – are to be met, a substantial new research effort is essential.

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REFERENCES CITED


BRADSTREET, M.S.W. and CROSS, W.E. Trophic relationships at high arctic ice edges. Arctic 35:1-12.


PIERSMA, T. and MORRISON, R.I.G. in prep. Energy expenditure and water turnover of high-arctic breeding Ruddy Turnstones in relation to climatic conditions.
RIZZO, B. 1990. The sensitivity of Canada's ecosystems to climatic change. Newsletter, Canada Committee on Ecological Land Classification 17:10-12.

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MUSKOXEN AND CARIBOU ON BANKS ISLAND:
A MODEL FOR PREDICTING
THE EFFECTS OF GLOBAL WARMING?

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ABSTRACT

The response of muskoxen (*Ovobos moschatus*) and caribou (*Rangifer tarandus*) on the arctic islands to global climate changes will largely depend on how their forage availability is affected. Warmer and moister summers will increase absolute forage availability. Plants will grow more in response to the warmth and moisture and the quicker rate of nutrient cycling which will alter the effects of grazing, especially by muskoxen. But, any increases in absolute forage availability could be counteracted. Warmer and moister winters may have catastrophic effects on relative forage availability if icing and deeper, denser snow impedes or prevents foraging. Spikes in the densities of the herbivores themselves may act as feedback mechanisms interacting with the weather to influence relative forage unavailability. Muskox and caribou have contrasting foraging and lactational strategies which explain, at least in part, their different responses to the weather, especially the timing of snowfall and the onset of greening vegetation which are key elements in the annual cycle of body condition. Muskox numbers surged on Banks Island from 3,000 to 37,000 while the caribou declined tenfold to less than 1,000 during the same two decades. Those decades were marked by a trend toward increasing snow depths but an earlier thaw. The muskox and caribou responses to trends in the weather on Banks Island hint at possible effects of global warming on the other arctic islands.

1 Anne Gunn (Ph.D.) has worked on the population ecology of caribou and muskoxen since the mid-1970s for the Canadian Wildlife Service and the Government of the Northwest Territories, most recently as the Regional Biologist for the Central Arctic.
POSSIBLE IMPACTS OF CLIMATE WARMING ON POLAR BEARS

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Canadian Wildlife Service
Edmonton, Alberta

ABSTRACT

Rapid warming of global climate could have serious consequences for long-lived species with low reproductive rates because they are unlikely to be able to evolve quickly enough to adapt to changes in their environment. Among polar species, the consequences for polar bears may be especially marked because climate warming will affect not only biological productivity of the marine ecosystem and the distribution and abundance of the seals they depend upon for food, but also the ice substrate that provides the essential platform upon which they hunt.

The first impacts of climate warming on polar bears will be felt at the southern limits of their distribution, such as in James and Hudson Bays where the whole population is already forced to fast for approximately four months when the sea ice melts during the summer. Prolonging the ice-free period will increase nutritional stress on this population until they are no longer able to store enough fat to survive. Early signs of impact will include declining body condition, lowered reproductive rates, reduced survival of cubs, and an increase in polar bear-human interactions. Although most of these parameters are currently detectable in the polar bears of western Hudson Bay, it cannot yet be determined whether or not climate change could be involved. In the High Arctic, a decrease in ice cover may stimulate an initial increase in biological productivity. Eventually; however, it is likely that seal numbers will decline if the quality and availability of breeding habitat is reduced. Should the Arctic Ocean become seasonally ice free for a long period, it is likely polar bears would become extinct.

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\(^2\) Andrew Derocher graduated in Forestry from the University of British Columbia and in Zoology from the University of Alberta. He studied grizzly bears in British Columbia and, since 1984, has studied polar bears in Hudson Bay and the Beaufort Sea.
CAN THE RINGED SEAL, PHOCA HISPIDA, BE USED TO MONITOR GLOBAL CHANGE IN THE ARCTIC?

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Nanaimo, British Columbia

ABSTRACT

The seasonal distribution, stability, and surface topography both of land-anchored and floating arctic sea ice, have major influences on the body condition, reproductive success, and cohort survival of the ringed sea, Phoca hispida. Short term changes in the extent of ice caused by meteorological conditions resulting in early freeze-up and late breakup can reduce marine productivity leading to severe declines in body condition, which results ultimately in decreased reproductive output. These conditions have prevailed several times over a 20 year period in the Canadian Western Arctic. At the other extreme, where conditions occur that prevent formation of stable land-fast ice, or where this ice is broken up during the winter months, such as in the Norwegian Arctic, ringed seals suffer large scale pup mortality.

The ringed seal, high in the Arctic marine trophic pyramid and tied ultimately to sea ice conditions, could, at first glance, be considered a prime candidate to be used as an indicator of the large scale effects of global warming. The complex influences, both positive and negative of heavier and lighter ice conditions emphasize the complexity of such models. The ringed seal example demonstrates that we must have detailed knowledge of the proximate factors influencing arctic populations prior to designing sampling schemes purporting to measure the effects of large scale phenomena such as global warming.

¹ Tom Smith is Section Head of Marine Mammals at the Pacific Biological Station. He has worked on ringed seals, polar bears, arctic foxes, and whales in the Canadian Arctic since 1967. His polar experience includes work in the Antarctic and, in recent years, in Spitsbergen as a research associate with the University of Oslo and the Norwegian Polar Institute. He holds adjunct professor status at McGill University and the University of Guelph where he supervises graduate students working on Arctic marine mammals.
CLIMATE CHANGE – IMPLICATIONS FOR ANIMAL AGRICULTURE

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University of Alberta
Edmonton Alberta
T6G 2P5

ABSTRACT

Climatic factors, including temperature, radiation, wind, relative humidity and photoperiod have major effects on ungulate species living outdoors. Cattle are adaptable to a wide range of environments; however, in cool temperate regions typical of Western Canada and in northern regions, feed energy requirements are substantially increased during winter. Increased requirements are due to acute cold stress aggravated by unfavourable wind chill, elevated resting heat production induced by prolonged cold exposure, and a reduction in feed digestibility. Within the thermoneutral range an increase of 1 °C in temperature due to global warming will decrease feed requirements of cattle by approximately 1% of the maintenance feed requirements. At temperatures below the animal’s critical temperature, an increase of 1 °C in temperature will decrease feed requirements of adapted adult cattle by about 3% of the maintenance requirements with a greater change occurring when there is wind. In warmer climates, reduced growth rates and increased maintenance energy requirements occur during summer in association with heat stress resulting from high ambient temperatures and solar radiant loads. Climatic warming in the order of 1-4 °C is unlikely to have much direct influence on ungulates such as cattle; however larger regional temperature differences may occur and such differences would have a greater impact on animal growth and efficiency. The indirect effect of global warming and changes in precipitation patterns on the productivity of forage plants upon which cattle and other ungulates depend for nourishment is likely to have a greater impact on animal agriculture than the direct effect of climate changes on the animals.

INTRODUCTION

Climatic factors, including temperature, radiation, wind, relative humidity and photoperiod have a large influence on animals living in outdoor environments, on the economics of maintaining suitable indoor environments for animals, and on the nature of the food supply available to them. In this paper, discussion will be primarily focused on how large domestic ungulate species which normally live outside throughout all seasons of the year respond to environmental and potential climate changes since data for nondomesticated ungulates is scanty. In order to restrict the scope of the paper, the effect of climate change on food supply will only be briefly considered in spite of the obvious importance of food to the animals. Numerous reviews concerning the effects of cold on animals are available (e.g. Webster, 1970; Young, 1981; Fuquay, 1981; Christopherson and Kennedy, 1983; Young et al. 1989). This subject has been reviewed most recently by Christopherson and Mathison (1992).

¹ Gary Mathison was born and raised on a mixed farm near Islay, Alberta. He is currently a Professor of animal nutrition in the Department of Animal Science. His current research interests are in the areas of digestive physiology and energetics.

² Robert Christopherson grew up on a family farm in southern Manitoba. He earned his Ph.D. degree in animal physiology from the University of Alberta in 1971. Dr. Christopherson is currently a Professor in the Department of Animal Science, University of Alberta.
INDIRECT EFFECT OF CLIMATE CHANGE ON ANIMALS

The largest impact any climate change will have on animals will undoubtedly be mediated through a change in food supply. Since there is some uncertainty concerning how the climate will change within the next hundred years, primarily because models differ about the potential effects of carbon dioxide on regional climates (DOE, 1990), there is a corresponding uncertainty about how the food supply will change and thus on the implications for animal agriculture. There have been suggestions, however, that both temperature and precipitation may increase in northern Canada in response to a global climate warming scenario (Smit, 1989). Such a scenario would mean increased plant productivity in northern regions which would translate into a greater capacity for animal populations. Since forages are better adapted and more productive in the marginal environmental conditions and on the relatively poor soils which exist in Northern Canada, the increase in animal population accompanying such a climate change would be primarily herbivores, such as indigenous ungulates. Predator populations would also increase and there would be a greater potential for animal agriculture involving domestic species such as cattle.

Even in the southern regions of Canada, an increase in wheat and corn production and a shift in some crop production from United States to Canada will characterize the trend towards global warming, according to some projections (Smit, 1989). Normally crop production is reduced in hot and dry climates; however productivity can be substantially increased if irrigation is used. A doubling in atmospheric carbon dioxide concentrations has been predicted to occur within the 21st century (DOE, 1990; MacCracken et al., 1990), and increased concentration of carbon dioxide has a beneficial effect on plants. Higher atmospheric carbon dioxide concentrations increase photosynthetic rates, increase dry matter yield, reduce stomatal conductance and improve water use efficiency, increase leaf area, and as well have other effects on C3 plants in particular (Sionit et al., 1981; Dahlman et al., 1985; Morison, 1989; Allen, 1990). Higher atmospheric concentrations of carbon dioxide can have a negative effect on plant nutritive value; however, since the N and mineral concentration in plant material dry matter may be reduced. Lincoln et al. (1984), for example, noted that the carbon to nitrogen ratio in soybean leaves was increased by 9% when atmospheric carbon dioxide was increased from 0.035% to 0.065%. A reduction in N content of forage plants could have serious consequences to animals in terms of reduced voluntary intake and productivity since existing plant material in Northern Canada already contains marginal levels of N, particularly during the senescence period.

DIRECT EFFECT OF CLIMATE CHANGE ON ANIMALS

The Effect of Warmer Winters on Animal Productivity: Estimates of climate change within the short term suggest that we might experience an increase in mean temperature of 1.5 to 4 °C by the middle of the 21st century (DOE, 1990; MacCracken et al., 1990) due to a projected doubling of atmospheric carbon dioxide from its preindustrial value and increase in other greenhouse gases with associated feedbacks. Temperature changes are expected to be greater in the winter than in the summer and at high rather than low latitudes and thus temperature increases of as much as 8 °C have been postulated for the Great Plains Region of North America in the next century (see MacCracken et al., 1990). Temperature increases in the northern regions of Canada are also expected to be considerably larger than the average global warming due to the melting of sea ice and snow cover (DOE, 1990).

The projected mean temperature increases due to climate change are relatively small in terms of the animal’s ability to compensate for them. However, in the winter, significant decreases in performance have been measured in animals that remain outdoors. Cattle performance data for states and provinces with cold winters (Figs. 1 and 2) indicate that winter daily gains ranged from 43 to 94% of that observed in summer, whereas feed requirements per unit of gain increased from 7 to 95% in the winter com-
sue regresses over the first 3 to 4 weeks of life, and is of little or no importance in adult ruminants which generate extra heat by shivering when they become acutely cold. The increased heat production is directly proportional to the decrement in temperature below the lower critical temperature and is inversely related to the insulation of the animal. Estimates of the additional requirements for metabolizable energy due to acute cold are given in Table 1 for cattle. Such estimates indicate that changes in temperature below the animal’s lower critical temperature can have a major effect on the efficiency of animal agriculture. Further, the information emphasizes the potential importance of changes in wind as a result of climate change since increases in wind not only raise the lower critical temperature of the animal but also increase the amount of heat required to maintain body temperature when the ambient temperature is below the critical temperature of the animal.

**The Energy Cost of Acclimatization:** The resting heat production of cattle, as measured in a thermoneutral environment, increases as a result of acclimatization to a cold environment for periods of one week or longer. The chronic increases in resting heat production for animals living in a cold environment are generally associated with increases in the capacity to tolerate severe cold stress (Young et al., 1989) and therefore are associated with survival during exposure to extremely cold environments. The elevated rate of metabolism due to acclimatization persists throughout the period of cold exposure and for at least one week after the animal is returned to a warm environment (Young, 1975). Qualitatively similar changes in resting heat production have been reported for sheep acclimatized to the outdoor winter environment (Webster et al., 1969) and for sheep acclimated to cold in controlled environment chambers (Graham and Christopherson, 1981). It should

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**TABLE 1. Increased heat production required to maintain body temperature per degree C the temperature falls below the lower critical temperature‖ Insulation Increased heat production per degree C**

<table>
<thead>
<tr>
<th>Animal</th>
<th>Insulation (°C.MJ⁻¹.m².d⁻¹)</th>
<th>Increased heat production per degree C (KJ kg⁻⁰.⁷⁵.d⁻¹)</th>
<th>(% of maintenance)²</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>No wind</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>newborn calf (30 kg)</td>
<td>3.23</td>
<td>21</td>
<td>4.4</td>
</tr>
<tr>
<td>month old calf (40 kg)</td>
<td>4.18</td>
<td>16</td>
<td>3.3</td>
</tr>
<tr>
<td>yearling (400 kg, summer)</td>
<td>4.24</td>
<td>13</td>
<td>2.7</td>
</tr>
<tr>
<td>yearling (400 kg, winter)</td>
<td>4.96</td>
<td>11</td>
<td>2.3</td>
</tr>
<tr>
<td>adult cow (600 kg, summer)</td>
<td>4.78</td>
<td>11</td>
<td>2.4</td>
</tr>
<tr>
<td>adult cow (600 kg, winter)</td>
<td>5.50</td>
<td>10</td>
<td>2.0</td>
</tr>
<tr>
<td><strong>13 km h⁻¹ wind</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>newborn calf (30 kg)</td>
<td>1.91</td>
<td>35</td>
<td>7.5</td>
</tr>
<tr>
<td>month old calf (40 kg)</td>
<td>2.87</td>
<td>23</td>
<td>4.9</td>
</tr>
<tr>
<td>yearling (400 kg, summer)</td>
<td>2.93</td>
<td>19</td>
<td>4.0</td>
</tr>
<tr>
<td>yearling (400 kg, winter)</td>
<td>3.53</td>
<td>15</td>
<td>3.3</td>
</tr>
<tr>
<td>adult cow (600 kg, summer)</td>
<td>3.46</td>
<td>16</td>
<td>3.2</td>
</tr>
<tr>
<td>adult cow (600 kg, winter)</td>
<td>4.06</td>
<td>13</td>
<td>2.8</td>
</tr>
<tr>
<td><strong>26 km h⁻¹ wind</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>newborn calf (30 kg)</td>
<td>1.55</td>
<td>44</td>
<td>9.2</td>
</tr>
<tr>
<td>month old calf (40 kg)</td>
<td>2.51</td>
<td>27</td>
<td>5.6</td>
</tr>
<tr>
<td>yearling (400 kg, summer)</td>
<td>2.57</td>
<td>22</td>
<td>4.5</td>
</tr>
<tr>
<td>yearling (400 kg, winter)</td>
<td>2.81</td>
<td>20</td>
<td>4.1</td>
</tr>
<tr>
<td>adult cow (600 kg, summer)</td>
<td>3.11</td>
<td>17</td>
<td>3.6</td>
</tr>
<tr>
<td>adult cow (600 kg, winter)</td>
<td>3.55</td>
<td>16.1</td>
<td>3.4</td>
</tr>
</tbody>
</table>

¹ Estimated from average insulation values given in NRC (1981) and assuming a hair coat length of 10 mm in the summer and 20 mm in the winter.

² Maintenance energy requirement estimated as 480 kJ kg⁻⁰.⁷⁵.d⁻¹.
be noted; however, that in a recent study Birkelo et al. (1991) did not find an elevation in resting or fasting heat production in winter even though there was reduced growth rate and increased energy requirements of steers. The reason for this contradictory result is not clear although the latter study was conducted in Colorado where the winters are less severe than in Western Canada. Perhaps the steers in the Colorado environment showed a form of habituation to fluctuating temperatures as described by Slee (1970) rather than metabolic acclimatization. Also, the possibility of an interaction of temperature with effects of photoperiod cannot be ruled out.

The magnitude of the change in resting metabolic rate due to acclimatization is quite large; it is suggested that for cattle energy requirements for maintenance are increased by 0.91% for each °C decrease in temperature across a wide range of temperatures, both in and below the thermoneutral zone (National Research Council, 1981). The validity of assumption that changes in resting heat production are linearly related with adaptation temperature has received support from studies in sheep (Whitmore and Young, 1986). Such changes in energy requirements are obviously major in nature, and therefore temperature changes which are expected to occur due to global warming will cause significant and measurable improvements in animal production efficiency due to the effect on resting heat production.

Effects Of Temperature On Digestion: As the environmental temperature decreases the apparent digestibility of dry matter and organic matter decreases for a wide range of forage-based diets (Christopherson and Kennedy, 1983; Christopherson, 1985; Kennedy et al., 1986a). The decrease is approximately 0.20 digestibility units per °C (with a range of 0.02 to 0.46) for shorn sheep, 0.05 units for fully-fleeced sheep, 0.20 units calves and 0.10 units per °C for larger steers and cows. If forage with an apparent

<table>
<thead>
<tr>
<th>Species and diet</th>
<th>Temperature range (°C)</th>
<th>Digestible</th>
<th>Metabolizable</th>
<th>Urinary</th>
<th>Methane</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sheep</td>
<td>11 to 38</td>
<td>0.11</td>
<td>0.08</td>
<td>-0.43</td>
<td>0.85</td>
<td>Blaxter et al. (1959)</td>
</tr>
<tr>
<td>Shorn, 600 g d-1 cubes</td>
<td>13 to 38</td>
<td>0.04</td>
<td>0.39</td>
<td>-5.51</td>
<td>-0.47</td>
<td>Graham et al. (1959)</td>
</tr>
<tr>
<td>Shorn, 1200 g d-1 cubes</td>
<td>8 to 38</td>
<td>0.12</td>
<td>0.17</td>
<td>-0.66</td>
<td>0.48</td>
<td>Graham et al. (1959)</td>
</tr>
<tr>
<td>Shorn, 1800 g d-1 cubes</td>
<td>8 to 38</td>
<td>0.18</td>
<td>0.82</td>
<td>-0.58</td>
<td>0.40</td>
<td>Graham et al. (1959)</td>
</tr>
<tr>
<td>Shorn, hay</td>
<td>3 to 23</td>
<td>0.49</td>
<td></td>
<td></td>
<td></td>
<td>Kennedy and Milligan (1978)</td>
</tr>
<tr>
<td>Straw:concentrate (50:50)</td>
<td>5 to 21</td>
<td>0.10</td>
<td>0.32</td>
<td>-0.86</td>
<td>-0.99</td>
<td>von Keyserlingk and Mathison (1992)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Species and diet</th>
<th>Temperature range (°C)</th>
<th>Digestible</th>
<th>Metabolizable</th>
<th>Urinary</th>
<th>Methane</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cattle</td>
<td>-7 to 20</td>
<td>0.29</td>
<td></td>
<td>-0.32</td>
<td></td>
<td>Christopherson (1976)</td>
</tr>
<tr>
<td>Hay-grain (50:50), Nov</td>
<td>-5 to 18</td>
<td>0.08</td>
<td></td>
<td>-0.39</td>
<td></td>
<td>Christopherson (1976)</td>
</tr>
<tr>
<td>Hay-grain (50:50), Dec</td>
<td>-23 to 9</td>
<td>0.12</td>
<td></td>
<td>-0.54</td>
<td></td>
<td>Christopherson (1976)</td>
</tr>
<tr>
<td>Hay-grain (50:50), Jan</td>
<td>-20 to 16</td>
<td>0.20</td>
<td></td>
<td>-0.42</td>
<td></td>
<td>Christopherson (1976)</td>
</tr>
<tr>
<td>Hay-grain (50:50), Feb</td>
<td>-1 to 18</td>
<td>-0.05</td>
<td></td>
<td>-0.63</td>
<td></td>
<td>Christopherson (1976)</td>
</tr>
<tr>
<td>Hay-grain (50:50), Mar</td>
<td>-8 to 17</td>
<td>0.09</td>
<td></td>
<td>-0.62</td>
<td></td>
<td>Christopherson (1976)</td>
</tr>
<tr>
<td>Hay-grain (50:50), Apr</td>
<td>-1 to 21</td>
<td>-0.10</td>
<td></td>
<td>-0.15</td>
<td></td>
<td>Christopherson (1976)</td>
</tr>
<tr>
<td>Hay-grain (71:29), maintenance</td>
<td>-5 to 35</td>
<td>0.07</td>
<td>0.07</td>
<td>-0.12</td>
<td></td>
<td>Blaxter and Wainman (1961)</td>
</tr>
<tr>
<td>Hay-grain (71:29), submaintenance</td>
<td>-5 to 19</td>
<td>-0.32</td>
<td>-0.46</td>
<td>-0.56</td>
<td>0.21</td>
<td>Blaxter and Wainman (1961)</td>
</tr>
<tr>
<td>3000 g hay</td>
<td>20 to 40</td>
<td>0.03</td>
<td>0.07</td>
<td>-0.40</td>
<td>0.03</td>
<td>Rogerson (1960)</td>
</tr>
<tr>
<td>2000 g hay + 1000 g concentrate</td>
<td>20 to 40</td>
<td>0.07</td>
<td>0.17</td>
<td>-0.40</td>
<td>-0.30</td>
<td>Rogerson (1960)</td>
</tr>
<tr>
<td>3000 g hay + 1000 g concentrate</td>
<td>20 to 40</td>
<td>0.08</td>
<td>0.07</td>
<td>0.04</td>
<td>0.17</td>
<td>Rogerson (1960)</td>
</tr>
<tr>
<td>6000 g hay</td>
<td>20 to 40</td>
<td>-0.02</td>
<td>0.06</td>
<td>-0.09</td>
<td>-0.50</td>
<td>Rogerson (1960)</td>
</tr>
<tr>
<td>6000 g hay + 1000 g concentrate</td>
<td>20 to 40</td>
<td>0.02</td>
<td>0.09</td>
<td>0.03</td>
<td>-0.47</td>
<td>Rogerson (1960)</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>0.08</td>
<td>0.09</td>
<td>-0.14</td>
<td>0.03</td>
<td></td>
</tr>
</tbody>
</table>
digestibility of 60% was being consumed, these mean decreases correspond to a decrease in the digestible energy value of the feed of 0.33, 0.08, 0.33 and 0.17% per °C. All-concentrate diets, which are rapidly fermented, are less susceptible to changes in the retention time and their digestion is largely uninfluenced by environmental temperature (Degan and Young, 1980; Kennedy et al., 1982; McBride and Christopherson, 1984).

The reason for the reduction in digestibility in the cold is that retention time of particulate and fluid digesta is decreased in the rumino-reticulum (Westra and Christopherson, 1976; Kennedy et al., 1976; Kennedy and Milligan, 1978; Christopherson and Kennedy, 1983) and in the whole digestive tract (Warren et al., 1974). The reduced retention time of particulate matter in the rumino-reticulum limits time available for fermentation of the more slowly degraded components of the diet, such as fibre (Kennedy et al., 1976; Kennedy et al., 1986a).

Energy is lost in urine and as methane as well as in the feces. Table 2 summarizes data from several studies in which the effect of environmental temperature on urinary and methane energy losses and digestibility were measured. The data indicates that, as temperatures decreased, urinary energy losses increased an average of 1.6 and 0.14 % per °C for sheep and cattle, respectively. Even if the extremely high value of 5.5% per °C for sheep obtained by Graham et al. (1959) is removed from consideration, the mean value for sheep is still a 0.63% increase in urinary energy loss per °C for sheep. At this time, it not clear whether this apparent difference in urinary energy loss between cattle and sheep due to decreased temperatures is real, or due to the limited number of measurements which are available.

Methane production generally is decreased in cold environments; the data suggests that mean losses are reduced 0.24 and 0.03% for each degree C of temperature decrease for sheep and cattle, respectively (Table 2). A decrease in methane energy losses at low temperatures might be expected since decreased digestibility of diets results in less substrate being available for methane production by microorganisms. Passage rates of digesta from the rumino-reticulum are increased in cold-exposed ruminants and a negative correlation exists between passage rates and methane production (Okine et al., 1989). Further, the increase in the propionate to acetate ratio which has been observed with cold-treated animals (Kennedy and Milligan, 1978) also indicates a partial shift from methane to propionic acid production in the rumen (Fahey and Berger, 1988). Cattle data in Table 2 supports the observation of Graham et al. (1959) with sheep that methane production reaches a maximum at temperatures between 23 and 28 °C. There is also evidence that methane production is influenced to a greater extent by temperature when intakes are high than when intakes are low (Graham et al., 1959; Table 2).

The net result of environmental temperature on the metabolizability of the diet, i.e. the amount of useful energy which is available to the animal from the diet (Table 2), appears to depend upon whether the temperature is above or below the animal’s thermoneutral zone. At low temperatures, decreasing temperatures will reduce the metabolizable energy content of the diet, but not as much as might be predicted on the basis of the decrease in digestibility. Above thermoneutrality, changes in the metabolizability of the diet in response to temperature appear to be similar to the changes expected on the basis of changes in diet digestibility. As an approximation; however, it can be considered that a 1 °C change in temperature will change the energy value of feed by approximately 0.1% in cattle.

Overall Effect of Cold on Cattle in Northern Canada: The mean temperature in Edmonton averages −23.2 °C, in January (Environment Canada, 1982a), which suggests that adult cattle would only occasionally experience temperatures below their critical temperature during winter if they have a winter hair coat, are reasonably well fed, and are protected from the wind. Surprisingly, the mean January temperature in Inuvik of −34.8 °C (Environment Canada, 1982b), is not lower than the lower critical temperature of a well-fed animal adapted to this environment, although minimum temperatures (mean −39.2) are. However, as shown by esti-
mates in Fig. 6, there are substantial energy costs in the cold environments due to reductions in digestive efficiency and to the greater resting heat production which accompanies acclimatization. Such changes amount to about 1% per degree change in temperature (0.1% due to changes in feed digestibility and 0.9% due to changes in resting heat production).

**Reduced Productivity Due To Warmer Summers**

In regions with mild winters but high summer temperatures, such as Arizona, studies by Ray et al. (1969) have shown that average daily gains of cattle during winter are 14-34% higher than in the summer. The reduced growth and feed efficiency during summer was attributed to heat stress associated with high solar heat loads. The maintenance requirements of beef cows in Texas also appear to be reduced during the mild winters and elevated during the hot summers (Laurenz et al., 1991). Therefore, the effect of seasonal weather changes on cattle varies in different parts of the temperate zone.

The upper limit of the thermoneutral zone is the upper critical temperature and represents the temperature above which the animal becomes heat stressed and rate and efficiency of gain are decreased. Body core temperature often begins to increase at temperatures near the upper critical temperature. Animals which are heat stressed switch on active mechanisms of evaporative heat loss which include sweating and vigorous panting to increase evaporation from the body surface and the respiratory tract respectively (Robertshaw, 1985). Evaporation of water is the only effective means of dissipating the metabolic heat load as environmental temperature approaches body temperature (Yousef, 1985a) because sensible heat losses are limited by the diminishing thermal gradient from the body to the environment. Since vaporization of water from the surface of the skin and respiratory passages decreases when the relative humidity of the air is high, a combination of high ambient temperature and humidity imposes a serious stress upon an animal (Robertshaw, 1985).

With prolonged exposure to a hot environment animals may show some adaptive responses. For example, animals may reduce their metabolic rate after some time in the heat, perhaps as a consequence of reduced food intake, but perhaps also as a result of reduced thyroid hormone secretion (Yousef et al., 1967). A more important limitation to feed intake in warm environments is the increased heat production in animals which accompanies feed consumption (i.e. heat increment of feeding). The amount of heat which is produced as a result of the inefficiencies in feed energy utilization is dependent upon the type of feed given as well as upon the physiological state of the animal. The heat increment of feeding at the maintenance feeding level normally ranges from 31 to 42% of the metabolizable energy content of the feed (National Academy of Sciences-National Research Council, 1984), with higher heat increments occurring when low quality forages are fed. Of the metabolizable energy which is available for live weight gain, 53 to 70% will be lost as heat due to inefficiencies in use, with the largest losses occurring when forages rather than grains are consumed. Animals fed high fiber, forage-based diets, then, will be under greater heat stress than animals fed lower fiber diets in hot climates. A low fiber diet resulted in higher milk production and lower rectal temperatures than a high fiber diet when cattle were fed outdoors in studies of Davis and Merilan (1960), even though no differences were noted between diets when cattle were fed indoors under cooler conditions. Moose et al. (1969) noted that, at environmental temperatures above 25 °C, the high heat increment of feeding impaired the efficiency of utilization of high fiber rations relative to low fiber rations. Johnson (1991) notes that heat stressed cattle will refuse to eat forage but will continue to eat concentrate feeds; further evidence that feeds with a high heat increment are detrimental in a hot environment.

Problems due to excessively high summer temperatures are not expected to be a problem in northern Canada, even if global warming occurs since mean temperatures in July are 16.8 and 15.5 °C in Edmonton and Inuvik, respectively (Environment Canada, 1982a,b) and the upper
critical temperature of lactating cattle in the summer would probably be in the range of 25 °C (Yousef, 1985a). In southern Canada; however, increases in summer temperatures would result in greater heat stress to the animals during the day.

**Other Effects of Climate Change on Animals**

*Effect of Temperature on Feed Intake:* Feed intake is substantially reduced in hot environments which limits the availability of energy and other nutrients for growth and formation of animal products. Lower feed consumption occurs because passage rate of digesta from the forestomach is reduced and this reduces clearance of feed residues from the rumen which in turn limits consumption.

When ruminants have unlimited access to feed, they will increase their voluntary feed consumption in the cold, and the supply of substrates from digestion will increase in spite of the reduced digestive efficiency (Kennedy and Milligan, 1978). Kennedy (1985) and Chai et al. (1985) have shown that the voluntary intake of chopped forages is increased by 8 to 26% during cold exposure. The ad libitum intake of pelleted diets, which is initially higher than that of chopped forage, has been shown to increase gradually in the cold over a period of 3 weeks or longer (Kennedy et al., 1986a). The ability to increase feed intake is an important response for animals in a cold environment and provides the animal with considerable ability to not only survive but to achieve reasonable levels of productivity. It is likely that the increased intake in the cold is facilitated by the increases in digesta passage rates discussed earlier. In addition, the improved protein supply to the intestine might be a factor that helps to enhance voluntary feed intake in a cold environment (Egan, 1977).

Curiously, in some studies, cattle have not shown increases in voluntary food intake in response to cold climatic conditions. For example, Milligan and Christison (1974) did not observe higher feed intakes in feedlot cattle during winter compared to summer even though the cattle were obviously influenced by season as indicated by their reduced growth rates during winter. It is possible that the short photoperiod during winter provided a negative drive to feed intake and prevented the cattle from increasing intake during cold weather. In red deer feed intake was reduced during declining day lengths and increased in response to increasing day length (Blaxter, 1982). Recently, Walker et al. (1991) reported that sheep on a constant feeding level showed marked seasonal changes in metabolic rate with minimal values occurring in association with declining day length. Data reported by Christopherson et al. (1978) and Christopherson et al. (1979) suggests that bison, yak, Hereford, and Highland calves do appear to show small seasonal changes in metabolic rate, manifested as an increase in the spring, that could be interpreted as a response to photoperiod. Photoperiod may, therefore, constrain the metabolic and feed intake responses to cold in early winter but facilitate such responses in late winter and spring.

*Beneficial Effects of Cold On Protein Status and Glucose Supply:* The quantity of microbial protein synthesized in the rumen is often not influenced by cold exposure, even though the microbes ferment less organic matter and, therefore, less energy substrate. Hence the efficiency of rumen microbial protein synthesis is increased in the cold, although this is not always statistically significant (Kelly et al., 1989). As a result of the escape of more dietary protein and the improved efficiency of microbial synthesis, the quantity of non-ammonia N which enters the intestine each day, and is digested, is at least maintained and often increased during cold exposure (Kennedy et al., 1986a; Kelly et al., 1989). Cold exposure therefore tended to increase the amino acid composition of duodenal digesta by 17% when four forage diets were fed in the chopped form (Kennedy et al., 1986b). Kelly et al. (1989) also have demonstrated increased absorption of total amino acid N as well as increased net absorption of lysine, histidine, alanine and tyrosine from the small intestine per 100 g of organic matter digested in the animal in the cold environment. In addition to serving as substrates for protein synthesis, amino acids serve, along with propionate and other compounds, as substrates for gluconeoge-
nesis and as fuels for thermogenesis. Glucose flux is known to increase during cold exposure and, since ruminant animals consuming forage absorb little or no glucose from the gut, the availability of gluconeogenic substrates is important. This is especially true in the case of a growing, pregnant or lactating animal where glucose is required for provision of reduced NADP to support biosynthesis. Hence, in spite of a reduced digestive efficiency in the cold, the favourable shift in propionate to acetate ratio coupled with the greater supply of amino acids to the small intestine may help the animal to sustain productive processes in a cold environment.

The positive effect of cold on the protein and amino acid supply to the small intestine of the sheep would suggest that ruminants may be able to utilize diets with lower crude protein content in a cold environment since the digestion products seem to be enriched in amino acids relative to energy. Ames and Brink (1977) have suggested that animals undergoing thermal cold stress could be fed diets that contain lower protein contents than would be acceptable in animals in a thermoneutral environment. Such a concept has important implications for animals consuming forages produced in northern Canada under nitrogen limiting conditions; global warming will tend to make indigenous and introduced species more susceptible to protein and other nutrient deficiencies than they are at the present time.

SUMMARY AND CONCLUSIONS

Global warming on the order of 1 to 4 ºC, with accompanying changes in rainfall amounts and distribution, will have a major influence on feed production and also availability of water for direct consumption by animals. Therefore, indirect effects of global warming on feed and water availability will be more important than direct effects due to a changing of the thermal stress on animals. Overall, temperature increases due to climate change will be unlikely to exert a major direct effect on large ungulate species, given their broad thermoneutral zones, and their ability to adapt physiologically to a variety of climatic conditions. However, regional climate change may be greater than the mean global change, thus localized large and measurable changes in animal efficiency will occur. In northern regions of Canada the warmer winters and potential for increased feed production will have a positive impact upon animals. In the southern regions, the positive aspects of milder winters will be tempered by greater heat stress in the summer so the overall effect on productivity may be small. If climate change involves increased variations in temperature, wind or humidity, this will impact negatively since environmental variation tends to be more stressful to animals than constant conditions (Senft and Rittenhouse, 1985).

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REFERENCES CITED


GRAHAM, A.D. and CHRISTOPHERSON, R.J. 1981. Effects of adrenaline and noradrenaline on the heat production of warm- and


KENNEDY, P.M. 1985. Influences of cold exposure on digestion of organic matter, rates of passage of digesta in the gastrointestinal tract, and feeding and rumination behaviour in sheep given four forage diets in the chopped and pelleted form. *British Journal of Nutrition* 38:159-173.


WESTRA, R. and CHRISTOPHERSON, R.J. 1976. Effects of cold on digestibility, retention time of digesta, reticulum motility and thy-


DENE KNOWLEDGE ON CLIMATE:
COOPERATIVE RESEARCH IN LUTSEL K’E,
NORTHWEST TERRITORIES

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BACKGROUND AND CHRONOLOGY

In October 1991, the Dene Cultural Institute (DCI) and the Arctic Institute of North America (AINA) proposed that a joint study of Dene indigenous knowledge on climate variability and climate change be incorporated into the Mackenzie Basin Impact Study (MBIS). MBIS agreed to fund the development of a community partnership and the research proposal. Subsequently, AINA and DCI asked the authors to undertake community selection. Criteria for a community partnership included strength of indigenous knowledge within the community; the community’s interest in and support for the work; the availability of potential research trainees in the community; previous experience with indigenous knowledge research; and the inevitable concerns with cost of access and work space available for the project. We considered a list of potential communities and decided to approach Lutsel k’e (Snowdrift, N.W.T.) first. We described the project to people in the community by phone and FAX throughout July 1992. We began field work by renewing acquaintances and meeting new people at the Desneche Spiritual Gathering that Lutsel k’e has organized each summer for the last five years. Nearly 500 people come to the gathering, near the east end of Great Slave Lake, from all over southern Denendeh and northern Saskatchewan. After the gathering we returned to Lutsel k’e (traveling by boat with people from the community and collecting weather variability data on Great Slave Lake).

During our first week with people in Lutsel k’e, it became evident that renewed empowerment, sustaining connections to the land, and community healing are very important to Lutsel k’e. People spoke about maintaining and strengthening knowledge about the land, and the sense of well-being and spirituality they derive from the land. The interest people have in self-determination, coupled with their continued participation in bush life, gave us the impetus to commit the other research partners to this community.

After the Desneche Gathering, we spent four days in Lutsel k’e discussing the project with elders and other people. We had planned to meet with Chief Antoine Michel and the Band Council about the project, but this idea was preempted by meetings of the South Slave Regional Council (SSRC) held while we were there. We proposed the project to the SSRC, and after questions and discussion, the SSRC and representatives from Lutsel k’e agreed to participate in the work. We returned to Lutsel k’e in late September to work on community awareness. During that visit we described the project during a public meeting, interviewed elders, and spent time with elders and students during the Lutsel k’e Dene School’s Cultural Inclusion activities.

We are now in the process of raising funds to conduct the research. Lutsel k’e expects us to

¹ This is a progress report on the research partnership between the Dene Cultural Institute (DCI), the Arctic Institute of North America (AINA), and the Lutsel k’e Dene Band. Not for citation or use without permission of the authors and the Lutsel k’e Dene Band.

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return, and knows that the primary research will be done by local people whom we will train in research methods. In December 1992, we hope to recruit people to a Community Advisory Committee for the project, to make formal the guidance we have received in combining the research with the community's interests.

OBJECTIVES

We are still working with Lutsel k’e on objectives that express the spiritual Dene relationship with the land, and the Dene perspective on changes in environment and climate. As people in the community take over guidance of the research, the objectives will come to express more clearly Dene perspectives on climate. The following objectives were developed for the first project funding proposal.

1. Record Dene indigenous knowledge on climate change and climate variability, building on recent research with Dene traditional environmental knowledge.

2. Collaborate with scientists working on the Mackenzie Basin Impact Study so that Dene indigenous knowledge is included in the MBIS, and policy decisions stemming from it.

3. Develop methods for organizing and accessing indigenous knowledge once it is recorded from elders and harvesters, so that it remains easily accessible and sustainable in communities.

4. Contribute to knowledge on the theoretical and methodological problems posed by efforts to integrate indigenous and scientific knowledge.

Learning Dene concepts that are significant to Dene perception of and response to climate is implicit in these objectives. Lutsel k’e Dene speak of the world holistically, and emphasize maintaining their relationship with the land for well-being, and for healing the individuals and collective wounds inflicted throughout contact with Eurocanadian culture. In the Fort Good Hope Traditional Environmental Knowledge project, Johnson & Ruttan (1992) found that climate, population cycles, and relationships between many parts of the natural world are significant to Dene environmental knowledge. Dene use many indicators to evaluate environmental conditions. Among these, it is important to understand the organisms and environmental components that possess spiritual power, how this power is used, and the spiritually-based rules that govern human interaction with nature.

Initial, semi-structured interviews and participant-observation on the land yielded clear evidence, not unexpectedly, that Lutsel k’e Dene consistently observe indicators of climate variability. These include quantity, quality, and duration of snow and ice, animal and bird movements, temperature, air quality; decisions people make about travel, hunting and trapping patterns and seasonal activities. Data on climate variability are embedded in the context of oral history and present accounts of harvesting. Searching for categories of Dene knowledge for collaboration with scientists requires interpreting these categories within holistic Dene knowledge. We cannot completely isolate aspects of Dene knowledge for integration with science because out of context they lose meaning. The challenge is extracting the climate data from the context. This is contrary to the way Dene participate in the natural world, but is possible for purposes of the MBIS.

THEORY AND METHODS FOR THE RESEARCH

Theory

Recent research and co-management strategies in the North have been directed towards the integration of indigenous knowledge with science (Report of the Traditional Knowledge Working Group, Government of the Northwest Territories, 1991). Without sound theoretical arguments supporting this work, such efforts will rely on political will rather than on the pursuit of knowledge and truth. The risk is that indigenous knowledge will remain subordinate to science (Johnson, 1992:5; Cizik, 1990:26).

Researching Dene knowledge about climate is an example of comparing indigenous knowledge with scientific knowledge. Philosophy of science provides a body of theory for interpreting the comparison of indigenous knowledge and scientific knowledge. Rational, relativist or
realist interpretations each have different implications for evaluating the validity of indigenous knowledge and science (Bielawski, 1992:6-7). Briefly, realist theory allows that indigenous knowledge contributes equally with science to our understanding of the world, but that each form of knowledge has a different relationship with its cultural context (Sayer, 1984). A realist view contrasts with culturally relativist interpretations more commonly invoked in describing indigenous knowledge. Anthropology is ideally suited for realist inquiry about science and indigenous knowledge (Jarvie, 1986:162-171).

Method

The research partners are committed to Participatory Action Research (Ryan and Robinson, 1990). The primary features of this approach are that the community guides the research; that indigenous local researchers are trained to do the research; and that the community maintains control of the research results. Strategies for research and collaboration include Dene researchers learning the appropriate way to elicit information from elders. Several community members have already described how elders assess the ability, and readiness, of younger people to receive information. Elders reveal information when it is appropriate to do so and the younger people are ready to learn it. Data collection will take place in semi-structured interviews and participant-observation on the land. The Community Advisory Committee, elders, trainees and the investigators will prepare the interview and participant-observation guidelines. The data sought are Dene indicators of environmental conditions, decisions in light of these indicators, and significant historical events that are evidence of climate variability and responses to it. In collaborating with the MBIS, we will compare oral history with scientific records of climate indicators.

MAINTAINING ACCESS TO INDIGENOUS KNOWLEDGE

Indigenous knowledge researchers, and people attempting to include such knowledge in research and policy, know that collecting indige-
rous knowledge data is but one problem. Keeping it accessible to communities for present and future use is yet another problem. Thus our third objective is to organize (through transcribing and indexing) indigenous knowledge already recorded in Lutsel k’e; to add the data we collect to the database; and to design a means for sustaining the local, indigenous database so that the Lutsel k’e Dene Band, the Lutsel k’e Dene School, the Lutsel k’e Economic Development Corporation, and other community interest groups, and individuals can readily access and use the information. This will involve using computers to the extent that data are entered in word-processing format and indexed in a database management program. The system should include text-string searching. This feature allows people to search lengthy transcripts for every reference to the topic of interest. Text-string searching goes beyond indexing because it does not require that every topic of interest be identified when the material is entered into the database. It allows the research team to go back through recorded data for references to material that only becomes significant as understanding of the data grows.

We are interested in references to climate in this research; in the future, Lutsel k’e will likely require other specific information from the detailed indigenous knowledge researchers record now. The community will be able to search their indigenous knowledge database for references to any topic of interest. The key, however, is to keep the process for entering data and accessing it straightforward and easy to maintain, so that using the material relies on expertise that is in the community.

Developing this system will build on technology and expertise already available in the community; working with elders, the Community Advisory Committee and a Technical Advisory Committee to design a system that people can use easily and reliably; and research in accessing indigenous knowledge databases and sustaining them in isolated settings. The result should be transferable to other communities, to the South Slave Regional Council, and to the Dene Cultural Institute for its indigenous knowledge documentation.
CONCLUSION

This research partnership will build on the experience of previous and current Dene Cultural Institute and Arctic Institute projects for documenting Dene knowledge. These include the Gwich'in Language and Cultural Project (Ryan and Robinson, 1990) the Fort Good Hope Traditional Environmental Knowledge Pilot Project (Johnson and Ruttan, 1992), and current projects in Lac La Martre on traditional justice and medicine, and in Rae Lakes on traditional government. Mackenzie Basin Impact Study personnel recognize the need for aboriginal contributions to the study both for historical perspective and future policy. The practical, theoretical, philosophical and moral validity of indigenous knowledge is supported globally (Altran, 1990; Barnaby, 1987; Benally, 1987; Bielawski, 1992, 1984; Colorado, 1988; Cruikshank, 1981, 1984; Freeman, 1992; Freeman and Carbyn, 1988; Hobson, 1992; Johnson, 1992; Johnson and Ruttan, 1992; Merculieff, 1990; Overing 1985; Salmon, 1985; Sayer, 1984; Waldrum, 1986).

The Lutsel k'e research will evolve in partnership with the community as the work is done. The partnership legacy will be documentation of Dene Sonzine knowledge, specifically about historical and cultural responses to climate, and community empowerment through participation in the research process.

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REFERENCES CITED


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REGIONAL ASPECTS OF GLOBAL WARMING: 
THE ROLE OF BIOLOGICAL RESEARCH 
IN THE MACKENZIE BASIN IMPACT STUDY (MBIS) 

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ABSTRACT 

As part of the Government of Canada’s Green Plan, the Global Warming Science Program includes a study of regional impacts of global warming scenarios in the Mackenzie Basin (MBIS). MBIS is focusing on potential climate-induced changes in the land and water resource base, and the implications of four scenarios of global climate change on land use and economic policies in this region. These policy issues include sustainability of native lifestyles, economic development opportunities in agriculture, forestry and tourism, sustainability of ecosystems and interjurisdictional water management. 

This presentation serves to outline the role of biological research in MBIS. This component includes studies of the Boreal ecosystem, terrestrial wildlife and freshwater fisheries, the development of a climate change scenario from proxy data, and the incorporation of native “traditional” knowledge into the data base. The main objective is to provide linkage between four global warming scenarios and regional policy by translating these scenarios in terms of biological impacts. Results from this component will be important on their own, but will also serve as inputs to other MBIS research activities focusing on land capability and economic development.

BACKGROUND AND OBJECTIVES 

This presentation focuses on the role of biological science in the development of a framework for an integrated regional impact assessment of global warming scenarios in the Mackenzie Basin, to be called the Mackenzie Basin Impact Study (MBIS). This watershed is the twelfth largest drainage area in the world, with important natural boundaries which may shift in response to climatic change. These include tree lines at the northern and southern extent of the boreal forest, as well as the discontinuous and continuous permafrost zones. There are large deltas, wetlands and lakes, which provide habitat for many terrestrial and freshwater species of wildlife.

The Mackenzie is also the most populated region of Canada's North. Energy development is an important component of the region’s economy, and there is growing interest in forestry, agriculture and tourism. There is also, however, a strong interest among native people to maintain their traditional lifestyles, and the political landscape is beginning to reflect that, through the land claims negotiations and devolution of management responsibilities from federal to regional authorities (Bone, 1992).

MBIS is attempting to address the “What If” question. What if global warming does occur as projected by General Circulation Model (GCM) simulations? What if international emission

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reduction and afforestation efforts fail to stop the rise in greenhouse gas concentrations? Since this is a regional scale socio-economic "What If" study, considerable attention has focused on defining the mission of MBIS. Scientific uncertainties exist in all aspects of this issue, from regional climatic data bases and GCMs, to our knowledge of cold region hydrological processes, boreal ecosystems, and sensitivities of northern communities to climatic variability. Concern has also been expressed regarding the context of climatic change, given the myriad of other changes that are likely to take place during the next several decades, include new technology, population growth, and political, institutional and economic changes.

At the organizational meeting held in 1990, the following Statement of Goals was adopted: "The Mackenzie Basin Impact Study will define the direction and magnitude of regional-scale impacts of global warming scenarios on the physical, biological and human systems of the Mackenzie Basin, using an integrated multidisciplinary approach. The Study will also identify regional sensitivities to climate, inter-system linkages, uncertainties, policy implications and research needs. Study results will be published and made available to all interested parties."

The key elements in the above statement are integrated, multidisciplinary, and policy implications. There is a growing trend in the international scientific community towards multidisciplinary investigations that are more suited to dealing with the complex nature of the global warming issue.

IDENTIFICATION OF POLICY ISSUES

Why was MBIS initiated? Why has it received support from the Government of Canada's Green Plan? Despite the many scientific uncertainties, there is consensus that increases in the concentration of carbon dioxide and other trace gases will lead to a warmer climate, but that it will take many years before these uncertainties will be reduced. What should be done while the climate modellers continue to work on their models? Although some have taken a "wait and see" approach, it is important to point out that policy making goes on. Land use plans are drawn, pipelines are designed, land claims and treaty rights are negotiated, afforestation options are being considered, and water management agreements are being established. In addition, we should not forget the ongoing efforts leading up to the United Nations Conference on Environment and Development (UNCED), which took place in Brazil in June, 1992. More than 150 nations negotiated global agreements, including a convention on climate change.

What difference would global warming make to resource management decisions being made in the Mackenzie Basin? The time scale of these and other policy concerns are of similar length to most scenarios of global warming, but decisions have to be made in the context of information available today, not 20 years from now.

MBIS, and other similar efforts, exist because there is a need to provide a regional, human perspective on global warming (Cohen, 1992). There is a bridge that needs to be built between global warming science and regional policy interests, so that decision makers can make informed judgements. There will always be scientific uncertainty, but there must not be an information vacuum. Otherwise, unsubstantiated claims will be made, and in the absence of alternative views, these may be acted upon.

In that spirit, MBIS formed an integration sub-committee which continues to play an important role in helping MBIS become an interdisciplinary effort that can focus on questions that are important to policy makers. Sub-committee membership was drawn from participants in each of the study's main components (physical, biological, socio-economic). Besides facilitating information exchange between study participants, the sub-committee has also been looking at integrating science and policy. It was felt that an "integration workshop" was needed in order to identify the policy targets for MBIS.

A FIRST ATTEMPT AT INTEGRATION

An "Integration Workshop" was held February 25, 1992, at the University of Alberta in
freshwater fisheries by Welch and Hamilton, and Melville will contribute to this effort.

MBIS will probably not be able to fully address water quality. There is another program, the “Northern River Basins Study,” or NRBS, which is expected to provide considerable information on current water quality in the Peace, Athabasca and Slave subbasins (NRBS, 1992). We anticipate that the two programs will be exchanging information. A similar exchange of information in anticipated with a long-term program focusing on hydrological processes in the Mackenzie, known as the Canadian component of the “Global Energy and Water Cycle Experiment,” or GEWEX.

**Sustainability of Native Lifestyles**

One major concern within the downstream jurisdictions of the Mackenzie Basin is the potential implications of a warmer climate on native communities and traditional lifestyles. For those who see their future as one in which subsistence (hunting, trapping, fishing) continues to hold an important place in their lives, adapting to a change in climate would require knowledge of how renewable resources might change.

Biological research contributes to this effort both through “modern” science and native traditional knowledge of how the biological environment has changed in the past. The latter include efforts by Bielawski and Masuzumi, and Aharonian to organize studies of traditional knowledge in communities of the Dene in the Northwest Territories. Studies of Boreal wetlands by Bayley *et al.*, terrestrial wildlife by Latour (response to burns) and Russell (a contributed study on the Porcupine caribou herd), fisheries by Welch and Hamilton, and Melville, will also be relevant. Additional insights will be obtained from one of the MBIS integration activities, Yin’s Integrated Land Assessment Framework (Section 4).

**Economic Development Opportunities**

Many see Canada’s North as the land of opportunity. The region has abundant fossil fuel resources, minerals, renewable resources (forest products, water, fish and wildlife), and could also become a more popular tourist destination. A warmer climate could increase the potential for development of agriculture. In scenarios of climate change, how significant could these opportunities become, and what would the potential side-effects be on existing land and resource uses? What might happen to the region’s settlements, including its native settlements and resource towns? What are the implications for defence policy and operations?

MBIS participants have initiated several activities that include biological studies. These include agriculture by Brklacich, and forestry by Benton and collaborators. These and other MBIS activities described above will contribute information to the integration activities, including the resource accounting framework (RAF) being developed by Lonergan *et al.*, and Yin’s Integrated Land Assessment Framework or ILAF (Section 4). These two frameworks will serve to explore indirect linkages between climate change and the region’s economy.

**Buildings, Transportation and Infrastructure**

The region is a vast sparsely populated land. Buildings, pipelines, offshore energy platforms and other infrastructure have been designed to meet the challenges of a cold climate and its associated landscape features, including permafrost, snow and ice. This combination of climate and population has led to the development of utilidors which provide water services in the larger communities. There is also a unique system of winter roads, an inexpensive transportation link between many northern communities which would otherwise be more isolated. These roads depend on a stable snow and ice cover persisting for 3-4 months. During summer, these communities can only be reached by water and air. The all-season road network is gradually expanding, with a new road to Wrigley expected to be ready by 1994, but other communities such as Norman Wells are still waiting.

If the climate warms, what would happen to permafrost, snow and ice? Some areas are already experiencing erosion, thaw settlement and other landscape changes due to past climatic variations. Could these changes accelerate in
the future? Could there also be changes in the annual hydrologic cycle which could change the nature of flood and low flow events?

Any of the above changes could have implications for the design and maintenance of buildings, onshore and offshore energy platforms, roads and other infrastructure. Within MBIS, this is one issue where biology will likely not play a significant role. The focus will be on permafrost, sea ice and hydrology.

Limitation Strategies

The Framework Convention on Climate Change, a product of the Earth Summit, was signed by the Government of Canada at the Earth Summit. It calls for the eventual stabilization of CO₂ and other trace gas emissions. This would affect emissions originating from transportation, agriculture, energy and other industrial activities. Any regional component of a national limitation strategy would have to account for its current and anticipated future mix of emitters.

What complicates matters in the Mackenzie is the interjurisdictional nature of the watershed, and potential changes in sources and sinks of trace gases due to possible changes in the landscape which may result from global warming. MBIS will include a number of activities focusing on the future of the region’s ecosystems (see Section 3.6). The studies by Bayley et al., and Benton and collaborators will provide some indication of how the carbon cycle may be affected by a warmer climate. MBIS does not include a specific activity focusing on anthropogenic (e.g. industrial) emissions.

This is a particularly difficult issue, and we do not expect to provide firm answers within MBIS. Other research programs, such as “BOREAS” and “NBIOME” are undertaking more detailed investigations of the carbon cycle in the boreal zone.

Sustainability of Ecosystems

The region includes tundra, boreal forest, wetland, delta, montane, sub-alpine and agricultural ecosystems. Each of these exist because of unique combinations of climatic, site and, in some cases, human influences. There is paleo-

ecological evidence that when climate changed in the past, vegetation responded, particularly in transition zones or “ecotones” which separate one ecosystem from another (e.g. arctic tree-line).

Several parks and wildlife sanctuaries have been established within the Mackenzie Basin’s boundaries, including a) Jasper, Wood Buffalo and Nahanni National Parks; b) Mackenzie Bison and Kendall Island Bird Sanctuaries; c) Peel River and Reindeer Grazing Reserves. Agricultural lands extend throughout the Peace River region of Alberta and British Columbia.

If the climate warms, there could be changes in growing season, hydrology, snow and ice cover, and fire frequency. Ecosystems would be sensitive to these changes, but at what rate? Would tree line shift northward? Would the boreal forest become much smaller in area (Rizzo and Wiken, 1992)? What would be the implications for forestry operations, park management, fire protection and wildlife management? These concerns overlap with native lifestyle and economic development issues, outlined above. MBIS activities that are relevant to concerns about ecosystem sustainability include

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<th>MBIS VERTICAL INTEGRATION MATRIX</th>
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Note: P1: Interjurisdictional Water Management
P2: Sustainability of Native Lifestyles
P3: Economic Development Opportunities
P4: Infrastructure/Transportation
P5: Limitation Strategies
P6: Sustainability of Ecological Systems

Figure 2. MBIS vertical integration matrix.
the study on Boreal wetlands by Bayley et al., lake thermal habitats by Melville, Mackenzie Delta shorebirds by Gratto-Trevor, wildlife response to burns by Latour, fisheries inventory by Welch and Hamilton, and arctic tree line fire by Wien et al. MBIS is fortunate to also be receiving contributions of valuable information on migratory geese from Marouf, and on the Procupine caribou herd from Russell.

**Linkages with Study Activities**

Following the integration workshop described above, a second workshop was held December 2-3, 1992 (shortly after the original version of this paper was presented). Integration matrices were constructed to show linkages between study activities and the six targets.

The Vertical Integration Matrix indicates linkages between socio-economic components and policy targets (Figure 2). The projects labelled "0" are data base and scenario construction activities, "1", "2" and "3" represent physical, biological and social science studies, respectively, and "4" represents integration modelling activities.

The Horizontal Integration Matrix identifies information needs from other activities within MBIS (Figure 3). For example, in order to determine the impact of climatic change on agriculture, one needs information on climate scenarios, erosion, land capability and other land uses from the "3" and "4" study activities. MBIS participants can also use this matrix to identify data which can be acquired from other studies.

**INTEGRATED ASSESSMENT**

As noted in Section 2 above, the RAF and ILAF are integration activities that seek to describe potential impacts on the regional economy and land uses, respectively. Both of these are still in the development stage, but it is important to note that biology will contribute inputs. The RAF requires an inventory of resources, including wildlife and wood products. MBIS activities will contribute to this

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Note: ID 0.1-0.4: Baseline and Scenario Conditions
ID 2.1-2.4: Biological System
ID 2.3-3.8: Socio-Economic System
ID 4.1-4.2: Integrated System

Figure 3. MBIS horizontal integration matrix.
Table 1: Northern Mackenzie

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Climatic patterns produced during these periods may provide useful data for the purposes of MBIS and other similar efforts.

A workshop on scenario development was held in January, 1992, at the Atmospheric Environment Service in Downsview, Ontario. Paleoclimatologists (including one of today’s panelists, G. MacDonald) and climatologists participated. Its purpose was to produce tables of temperature and precipitation for the study area, based on proxy evidence as well as data from the instrumental record for the site in question and another site that could serve as a “transpositional” or “spatial” analogue. The study area was split into three divisions (Figure 4) and tables constructed for each (e.g. Table 1).

The result of the exercise was that paleoclimatology provided useful information for ecotones during the growing season, but that it would be difficult to describe climatic conditions for winter. The analogue could not rely solely on instrumental data either, due to the short record.

The analogue scenario therefore became a “composite” analogue, incorporating information from paleoclimatology, the instrumental record for the site in question, and instrumental data from a warmer location (the “transpositional” or “spatial” analogue), where appropriate. The example in Table 1 illustrates the case of “Northern Mackenzie.”
Table 2: Mackenzie Valley

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**CONCLUSION**

Biological research plays a number of different roles in MBIS. It is used to investigate implications of climatic change for ecosystems, to generate scenarios of climatic change, and to provide data for the subsequent determination of socio-economic impacts for native communities and various commercial enterprises. All of these efforts provide a basis for discussion of potential implications of climatic change for regional policy.

This research effort is not confined exclusively to university trained scientists. MBIS is attempting to supplement “modern” science with native traditional knowledge of the environment.

Biology in its various and diverse forms of inquiry represents an important source of information for MBIS and other impact studies. This effort must continue as we attempt to build bridges between global climatic change and the concerns of regional stakeholders.

**REFERENCES CITED**


Lewis, G.D., D. Milburn and A. Smart. 1991. The challenge of interjurisdictional water man-
