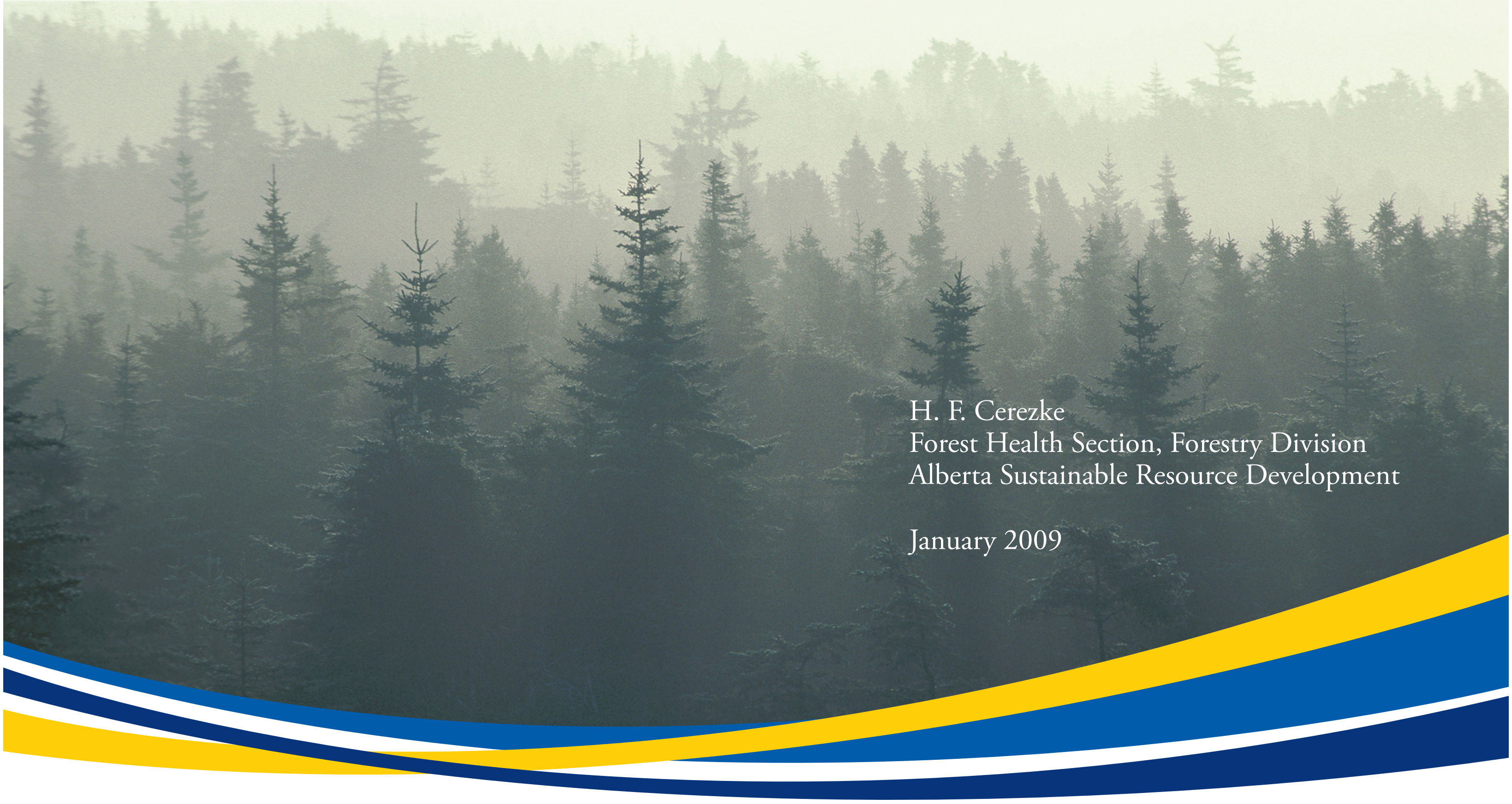
Climate Change and Alberta's Forests

An Information and Discussion Paper of Predicted Implications



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FORWARD AND ACKNOWLEDGEMENT

The growing awareness of global climate changes and the associated increasing concentrations of atmospheric greenhouse gas emissions have raised concerns about the future welfare of Alberta's forests and the forest land base. Forests are shaped by climate, in that climate determines what will grow, where it will grow and how well it will grow. Climate changes have been occurring, and further changes are predicted to continue to occur during future decades. As a consequence, global temperatures are rising and precipitation regimes are changing. These factors have the potential to dramatically affect forests province-wide in their distribution, productivity, function, composition, values and health. Implicit in these projections is the need to maintain long-term sustainable management of the forests and to maintain forest ecosystems in a healthy and resilient state. Significant challenges accompanying climate change are the many complex biological interactions associated with forest ecosystems and disturbances, among which are increased forest fire risks and predicted increased insect and disease outbreaks. These challenges will likely be significant and integral in the development of new forest adaptation and mitigation strategies in the future decades.

An important function of this report and its main objective are to collate and summarize information on potential climate change effects on Alberta's forests to help raise awareness of predicted impacts. The initiation of this project is credited to Hideji Ono, former Senior Manager of the Forest Health Section of Alberta Sustainable Resource Development, who foresaw the need to collate a broad spectrum of potential impacts of climate change on provincial forests and forest ecosystems as a framework for interpreting the many forest health related issues. For his timely recognition of this project and for helping to define the scope of coverage of the subject matter, I extend my sincere thanks and appreciation. I also express my thanks to the following staff at Alberta Sustainable Resource Development who kindly provided reviews and suggestions for improving this document: John Stadt, Leonard Barnhardt and Deogratias Rweyongeza, and to Harry Archibald with Alberta Environment for his comments and suggestions. I express thanks to Jan Volney and Ted Hogg, Natural Resources Canada, Canadian Forestry Service, for their helpful discussions and insights of this topic that helped me to develop the scope and reference sources for this paper. Lastly, I acknowledge the technical assistance of Linda Joy for transferring charts and maps and for her secretarial support services, and to Deanna McCullough and Rob Harris, Business Planning and Information Section, for editing and final draft preparation.

EXECUTIVE SUMMARY

This report collates and synthesizes much of the current information and scientific literature on the impacts of climate change on forests and forest ecosystems, with special relevance to the province of Alberta. Forest ecosystems are highly dependent upon climate for distribution of tree species, their growth, productivity and health, and are predicted to respond in a variety of ways to a changing climate. This report presents an overview of the major impacts predicted to occur during the 21st century. Based upon climate change projections for Alberta, significant impacts reviewed are in relation to tree species distributions, changes in forest ecosystems and biodiversity, wetland areas, growth and productivity responses of trees, disturbance events, forest genetics, invasive species, and with an emphasis on forest health-related issues. The main purposes of this report are to serve as an information source, to increase awareness of the potential impacts of climate change on Alberta's forest resources, and to stimulate further discussion.

Background information on the global carbon cycle, the dynamics of the carbon budget and current status of greenhouse gas (GHG) emissions is presented as a framework for understanding and interpreting biosphere energy relationships. Rising temperatures and GHG emissions are reviewed to indicate their influences on present and future climate scenarios. This information is extracted mostly from the Third and Fourth Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC, 2001, 2007a, 2007b).

Climate projections: Climate scenarios for Alberta are projected to the 2020's and 2050's and beyond for four climatic variables: mean annual temperature (MAT), mean annual precipitation (MAP), growing degree days >5°C (GDD), and an annual moisture index (AMI), calculated as the ratio of total annual degree days GDD >5°C to the total annual precipitation. By the 2050's, MAT is expected to rise by 3° to 5°C; MAP is projected to range between -10% and +15% with the largest decreases during summer; GDD may increase 30% to 50% and AMI will likely increase 20% to 30%. Winters are expected to be warmer with increased precipitation; spring and summer periods are predicted to be earlier with reduced soil moisture; and there will be a longer frost-free growing season. The climate is expected to be more variable with more frequent extreme weather events and increases in water scarcity.

Tree species and distribution predictions: Climate change projections beyond the 2020's for the prairie provinces indicate that climate variability and risk of extreme disturbance events, particularly drought, will be the most important threats imposed on forest ecosystems in Alberta. Other disturbance events (fire, insects, diseases, storms, etc.) predicted to increase will also be important. Increased water scarcity will impact the growth of tree species, their survival, productivity and distribution, especially at the southern boundary of the boreal forest where drought stress will be a main cause of tree decline contributing to regeneration failure, reduced growth and survival, and crown dieback. In contrast, growth and survival of conifers are predicted to increase at higher elevations in southwestern Alberta. Drier conditions are also forecast for much of the central and northern boreal forest. In response, tree species in general are expected to shift northward and to higher elevations, causing reductions in the ranges of boreal species. Engelmann spruce, subalpine fir and lodgepole pine may move to higher elevations, while alpine larch and whitebark pine may find suitable habitat by shifting northward; their distributions at higher elevations may be reduced. Many of the important commercial conifer species are expected to lose a portion of their currently suitable habitat, raising concerns that the present provincial forest land base will decrease.

Aspen forests in the southern boreal region particularly are expected to decline, shift northward, and suffer reduced productivity due to periods of drought and recurring insect defoliations. Some tree species such as Douglas-fir, ponderosa pine, western larch, Scots pine and Siberian larch may gain new suitable habitat in western Alberta.

Ecosystem and biodiversity predictions: Warming temperatures and projected increased evapotranspiration rates will impact the forest hydrology of wetland/peatland ecosystems by lowering the water table, favoring increased aerobic conditions, and increasing the rate of decomposition of accumulated dead organic plant materials. This will likely decrease the overall carbon storage and result in increased CO_2 and CH_4 releases in the atmosphere. The drying of some wetland/peatland areas, however, may create new habitat for white spruce, birch and aspen, replacing typical wetland inhabiting species such as willow, black spruce and tamarack.

Climate change is expected to affect the composition, structure and function of forest ecosystems by impacting their fundamental qualities, which include competition of species and succession, water use, nutrient cycling, disturbance regimes, and productivity. Responses to temperature change and increased CO_2 concentrations will vary within and among ecosystems in magnitude and direction, and forest ecosystems will be changed or modified in predictable and unpredictable ways. Impacts of climate change on forest biodiversity could be both positive and negative, even though overall diversity of ecosystems is predicted to decrease. Some species extinctions and reduced biodiversity will result, mainly from land-use changes, deforestation, and forest fragmentation.

Forest productivity predictions: Predictions of forest growth and productivity impacts due to climate change are somewhat unclear, but are likely to be positive in many situations due to lengthening of the growing season, increased soil and air temperatures, nitrogen deposition and nutrient cycling, more frost-free days, and the possibility of some CO_2 fertilization effects. However, growth and productivity will also be negative in some situations because of increased disturbance events, reduced moisture availability, and air quality impacts such as $O_{3.}$ The current general trend of net primary productivity in boreal temperate forests across North America is increasing but the continued long-term trend in future years is unclear. Forests in western Canada may persist in a carbon flux situation, shifting from one of sink to source, depending upon the frequency, duration and extent of forest disturbance events. In general, growth, survival and productivity of white spruce are predicted to decline in the central and northern parts of Alberta within the next 25-30 years. Site index and productivity of lodgepole pine forests in the foothills region have been increasing, but it is unclear whether these changes are attributed to improved management practices, to climate change influences, or to both. Provenance trials of conifers in Alberta have demonstrated that increased productivity is possible if more optimal climatic environments can be identified to allow realization of their genetic growth potential. Periods of drought stress and predicted increases in insect defoliator outbreaks could severely impact the growth, productivity, and health of aspen stands in the Boreal and Parkland zones.

GHG emission predictions: Atmospheric concentrations of GHGs (CO_2, CH_4, N_2 and tropospheric O_3) and their effects on tree growth and physiology have been reviewed. Numerous experiments have examined CO_2 concentrations of 475-600 ppm or parts per million (i.e., about 2x current atmospheric levels projected to occur by 2050 or 2100) and its effects on tree species. These effects, though highly variable, have ranged from increased ecosystem productivity to enhanced growth of tree structures, changes in wood anatomy, enhanced reproductive fitness, increased foliage nitrogen concentration, to an altering of the sensitivity of trees, making them more prone to the damaging impacts of O_3. Increased tropospheric O_3, on the other hand, is a growing air pollutant and a threat to forests in the northern hemisphere. Current concentrations range between 20 and 45 ppb (parts per billion), but are increasing, and concentrations >70 ppb appear to be detrimental to tree growth and health. High O_3 concentrations have been linked to reduced tree growth and productivity, a reduction in forest carbon sequestration, decreased nitrogen mineralization in the soil, and interactions with CO_2 levels that alter the susceptibility of trees to insect and disease species.

Forests are important sources of N_2O where it is produced in soils as an intermediate or end product from the biological nitrification and denitrification processes. At present, only about 7.5% of the total CH_4 emissions to the atmosphere is known to be contributed by forest ecosystems. The boreal forest has been reported as both a sink and a net source of CH_4 partly because emissions can vary seasonally due to land-use, soil temperatures and water table levels.

Forest disturbance predictions: Forest disturbances can be both human-caused (e.g., harvesting) and natural, including fire, drought, storms, insect and disease outbreaks, landslides and floods. Future forest fire disturbances are predicted to be more frequent, burn over larger areas and with increased severity. Besides killing trees and creating patches and fragmentation over the landscape, fires interrupt the process of forest biomass accumulation, shift the direction of forest succession, release GHGs to the atmosphere, cause a shift in carbon fluxes, and a shift to a younger stand age-class structure. Increased variability in weather systems is likely to result in more frequent and severe storms, periods of drought, areas of windthrow, and result in increased tree damages, dieback and mortality. Fire disturbances will interact with drought-stressed trees, decreased soil moisture, and increased insect/pathogen activity. Increased water scarcity leading to drought conditions is predicted to be the most serious climate risk for Alberta, impacting all ecosystem functions. Changes in temperature and precipitation will affect the life histories, dispersion, reproduction and population dynamics of forest insect species and the infection and epidemiology of tree pathogens. Species likely to be especially influenced favorably by climate change include the mountain pine beetle, spruce beetle, spruce budworm, wood borers, root diseases and stem cankers. There will also be increased risks of other minor pests as well as risks of new pests and invasive alien species, and a likely increase in freeze-thaw injuries to trees.

Forest genetics predictions: Tree species may respond to climate change in one of three ways: by genetic adaptation, migration or extinction (Aitken et al. 2008). Because of their inherent genetic variability, tree species are likely to respond in a variety of ways. Those with relatively narrow variability, poor dispersal capabilities, or those occupying a limited range are most prone to extinction, especially in montane and alpine habitats. Genetic variation and the ability to adapt to environmental changes will be the most important criteria for survival. However, the maintenance of genetic diversity in species may be challenged by the shifting of tree distributions and forest habitat fragmentation. Tree species with wide natural ranges exhibit high genetic variation and therefore have a better chance of survival in a changing climate. The potential to migrate with a changing climate will differ for each species and will depend upon dispersal efficiency, suitable new habitats available, and available corridors for movement. Some species may require human assistance. Knowledge of climate factors affecting genetic differentiation will be essential for matching seedling populations to appropriate planting sites.

Invasive species predictions: Invasive or alien species not native to Alberta may include insects, pathogens or plants, many of which can often detrimentally affect all attributes of forest ecosystems. Invasive species such as white pine blister rust or mountain pine beetle kill or weaken trees, and alter the ecology, function and value of forest ecosystems. Increased human access, changes in land-use patterns, forest fragmentation and forest disturbance events all provide increased opportunities for invasive species to become established. Once invaded, their ultimate range may be largely determined by climate and human activities, and climate change will likely amplify their rate of spread, survival and competitiveness. There are numerous aspects of increasing temperatures, elevated CO_2 levels and precipitation changes that may give non-native alien species advantages over native species for successful establishment and survival.

Forest health predictions: The sustainable management of Alberta's forest resources under changing climate regimes will be challenged to maintain forests in a healthy condition and in carbon balance. Climate change threatens to increase forest disturbance events and to impact forest succession patterns such as in post-mountain pine beetle outbreak areas. As well, in areas of the Boreal and Parkland zones, drought, fire, insects, pathogens, and storm events will increasingly influence ecological succession changes in aspen and mixedwood forests. Increased forest disturbance events will reduce mature and overmature forests and shift them to younger age class structures. This will have the effect of decreasing the incidence of insect and pathogen species associated with mature trees and forests (e.g., bark beetles, wood borers, defoliators, root and stem rots and stem cankers), while increasing opportunities for pests attracted to young stands (e.g., needle cast and stem rust diseases, leader and root-collar weevils, and Armillaria root rot). Damages caused by abiotic influences are also expected to be more frequent and severe and include moisture deficiencies, freeze-thaw events and hail. Storm damages are forecast to be more severe and frequent, and will result in more frequent blowdown of mature forests with subsequent interaction with insects and fire. Although many of these impacts of climate change may be decades away, there is uncertainty in the magnitude and timing of future changes. Detection of climate change effects will require the implementation of a comprehensive inventory, monitoring and assessment system to detect and evaluate the vulnerabilities of the provincial forest resources to climate change. Such a system will be essential to developing adaptation strategies and mitigation measures.

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1.0 INTRODUCTION

Significant changes are anticipated to occur in Alberta's forests over the next several decades due to predicted increases in atmospheric temperatures and greenhouse gases. These climate change predictions are expected to impact Alberta's forests in a number of ways, ranging from shifts in tree species distributions, altered growth and productivity, increased risks of major disturbances (fire, drought, insects and diseases), loss of biodiversity, and potential loss of the forested and productive forest land base to changes in timber supply, water resources, recreation, tourism, and other socio-economic impacts. The changes are expected to be long term; are likely to affect all aspects of forest management; and will require innovative adaptive measures to help mitigate the impacts that the province will face.

Climate change has been described as a major environmental challenge, potentially affecting our lifestyles, health, economics and social well-being. Changes in climate have the potential to impact all regions of the world and virtually every economic sector (Bhatti et al. 2006a; Natural Resources Canada 2004). Climate is naturally variable and changes in climate have always occurred (Bhatti et al 2006a; Hengeveldt 2006). In the geological past (at least during the past 420,000 years), the earth has been subjected to sequential glacials, interglacials, and warm periods, and all parts of Canada have been warmer, cooler, wetter and dryer (Bhatti et al. 2006a). A number of factors control climatic variability including Earth's orbit, changes in solar output, sunspot cycles, volcanic eruptions and fluctuations in greenhouse gases (GHGs) and aerosols (Bhatti et al. 2006a; IPCC 2007a; Natural Resources Canada 2004).

Our present climate change has been described as unprecedented in both magnitude and cause and cannot be explained by these factors alone. Recently reported increase in global temperatures have been strongly linked to increases in the concentration of GHGs that have been largely attributed to human activities (Bhatti et al. 2006a; IPCC 2007a). During the course of the 20th century, global mean surface air temperature has risen 0.6°C and is projected to continue to increase at an average rate of 0.1° to 0.2°C per decade for the next few decades (Bhatti et al. 2006a; Natural Resources Canada 2004). Global average surface air temperature is projected to increase between 1.4°C and 5.8°C during the period 1990-2100 (Fig. 1, IPCC 2001). However, average temperature across Canada is expected to rise at twice the global rate (Bhatti et al. 2006a). Temperatures in Canada have generally been increasing steadily since the late 1940's, with winter temperatures rising above normal between 1985 and 2005, while during the same period, winter precipitation has been decreasing (Bhatti et al. 2006a; Hogg and Bernier 2005). The greatest warming during the 20th century has, however occurred in western Canada, with an up to 6°C increase in minimum temperatures. Consequently, the frequency of days with extreme high and low temperatures is predicted to increase, snow and ice cover to decrease, and heavy precipitation events to increase. Additionally, during the latter half of the 21st century, heat sums measured in degree days across southern Canada are expected to increase by between 40% and 100% (Bhatti et al. 2006a).

The projected climatic changes during the 21st century will significantly impact forest ecosystems and the forest sectors and communities dependent upon them (Johnston et al. 2006). This paper examines the implications and likely impacts of climate change on Alberta's forests projected over the next 30 or more years. Forest ecosystems are highly dependent upon climate for distribution, growth, productivity and health, and are predicted to respond in a variety of ways. Some important projections include the migration of some tree species northward and to higher elevations, new assemblages of species occurring in space and time, overall loss of biodiversity, changes in disturbance regimes (e.g., increased forest fire frequency and extent, increased wind and storm damages, and increased insect and disease occurrences), changes in forest productivity and age-class structure, hydrology, wetlands, and challenges in maintaining the productive forest land base and land use (Bhatti et al. 2006a; Johnston et al. 2006; Mortsch 2006; Natural Resources Canada 2004). The net impact of such climate-induced changes on forestry and forest-dependent communities in Alberta include a variety of biophysical and socio-economic impacts that could be both positive and negative.

2.0 SCOPE AND PURPOSE OF THIS DOCUMENT

The major objective of this paper is to collate and synthesize much of the current information and scientific literature on the impacts of climate change on forests and forest ecosystems relevant to the province of Alberta. Likely scenarios of future climate extending over the next 30 or more years in Alberta are reviewed. Predicted increases in global GHGs and aerosol emissions, rising temperatures and precipitation changes are reviewed and interpreted for their potential impacts on plant species, tree distributions, forest ecosystems, biodiversity, forest productivity, land-use issues and forest disturbances affecting forest health and structure. A summary of forest health issues forecast for Alberta is presented in addition to some forest management response options to help mitigate the effects of climate change. This paper is intended to serve mainly as an information source and as a basis for discussion.

3.0 GLOBAL CARBON CYCLE AND THE CARBON BUDGET

There is a fixed amount of carbon (C) on planet Earth that is distributed in five principal global C reservoirs or pools: these include the Earth's atmosphere, vegetation, soils, oceans and fossil fuels (Bhatti et al. 2006b; Oregon Wild 2007). Carbon, which is a fundamental requirement for all life on Earth, cycles through exchanges among the reservoirs of C on or near the Earth's surface (mainly in plants and soils), in the atmosphere (mainly as gases), and in water and sediments of the ocean. The reservoir sources of C are components of this cycle. Carbon is continuously cycled through and exchanged between reservoirs, being transferred from one to the other, with exchanges often in both directions and at different rates and time frames.

The global carbon budget is the balance of the exchanges (incomes and loses) of C between the carbon reservoirs or between one specific loop of the carbon cycle. An examination of the carbon budget of a reservoir can provide information as to whether the reservoir is functioning as a source (contributing C) or as a sink (removing or storing C). An understanding of the carbon budget, including sources and sinks, is critical to interpreting climate related issues.

The five principal global C reservoirs are listed in Table 1 with the total amount of estimated carbon, in gigatons [a gigaton or Gt is a billion (10^9) metric tons, 10^{12} kg, or about 2200 billion pounds]

Table 1. Summary of the global main reservoirs of carbon sources with estimated amounts of carbon in gigatons (Gt).

Reservoir of carbon	Size (Gt)
Atmosphere	807
Vegetation	610
Soils (total)	(2500)
Organic	1550
Inorganic	950
Surface ocean	1020
Deep ocean	38140
Fossil carbons (total)	(5000)
Coal	4000
Oil	500
Gas	500

Adapted from J.F. Kasting (1998) and Bhatti et al. (2006b).

In the atmosphere, C is stored as carbon dioxide (CO_2), methane (CH_4), and organic compounds. Carbon moves into the atmosphere from decomposition of organic matter, combustion, volcanic activity, respiration of live organisms, burning of fossil fuels, soil erosion, and other activities. Carbon moves out of the atmosphere through photosynthesis, rock weathering, dissolution in water and other means. All plants, including trees and many micro-organisms, use photosynthesis to take CO_2 out of the atmosphere and form sugars, cellulose, as well as other complex molecules that comprise plant biomass. This process is called primary production and enters the bottom of the global food chain, referred to as "primary productivity". Plants shed dead leaves and woody materials which contribute to soil carbon stores within the soil (Apps et al. 2006; Oregon Wild 2007).

Carbon in the biosphere is stored as live or recently dead plants, animals, and microorganisms in the ocean and on land (forests and soils). Forests dominate the terrestrial carbon cycle, storing 86% of the Earth's above ground C and 73% of the Earth's soil C. Carbon enters into the biomass pool via photosynthesis, cycles through the global food chain, then moves out of the biomass pool through decomposition and respiration, or through long-term storage as fossil deposits (Oregon Wild 2007).

In the oceans, carbon is stored mostly as dissolved CO_2 and other dissolved organic compounds that originated from some photosynthetic life form. Carbon moves into the ocean from the atmosphere and biosphere through dissolution of organic matter and CO_2, leaching, and input from river systems. Carbon moves out of the ocean mainly through photosynthesis and deposition in marine sediments.

In geological deposits, carbon is formed from long-dead plants and animals and stored as coal, oil and gas. Carbon moves into the fossil reservoir by deposition and storage in low-oxygen conditions, and moves out of the fossil reservoir mostly through exploitation and combustion. Non-fossil carbon is stored in limestone and other rocks. It moves into these geologic deposits mostly through ocean deposition such as from the shells of marine animals. Carbon moves out of this reservoir via volcanic activity and human industries such as in the manufacture of cement (Apps et al. 2006; Oregon Wild 2007).

The carbon cycle is the combination of many different physical, chemical and biological processes that transfer carbon between the various reservoirs. During the past millions of years, this carbon cycle was responsible for the formation of coal, petroleum and natural gas, the fossil fuels that are the primary sources of energy for our modern societies (King et al. 2007). Human anthropogenic activities have, however, since the start of the industrial revolution (about 1750) altered the Earth's carbon budget and created a carbon imbalance in the Earth's atmosphere, land, fresh water and marine environments (Apps et al. 2006). This imbalance has come about largely due to the combustion of fossil fuels and land-use changes such as deforestation that have released excess quantities of carbon into the atmosphere. The sum total of carbon in reservoirs is far greater than can be balanced by the biological and geological processes that naturally remove CO_2 from the atmosphere and store it in terrestrial and marine environments as part of the Earth's carbon cycle (through processes referred to as sinks) (Apps et al. 2006; IPCC 2007a; Oregon Wild 2007). Consequently, there has been an excess buildup of CO_2 concentration in the atmosphere, an increase of about 35% between 1750 and 2005, and it is presently higher than at any time in the past 420,000 years (Apps et al. 2006; IPCC 2000). Because of the importance of CO_2 as a greenhouse gas, the imbalance created between sources and sinks, and the subsequent increase in CO_2 concentration in the atmosphere there are now consequent changes in the Earth's climate. The recently recorded increases in CO_2 and other greenhouse gases are strongly correlated with observed increases in global temperatures (Bhatti et al 2006a). Carbon dioxide is considered to be the largest single forcing (refers to the amount of energy entering or leaving the climate system) agent of climate change (Hengeveld 2006; IPCC 2001).

4.0 GREENHOUSE GASES (GHGs) AND CLIMATIC INFLUENCES

The Earth's climate is powered by the Sun which provides radiating energy at very short wavelengths in the visible and near invisible part of the spectrum. About one-third of the solar energy reaching the Earth's atmosphere is reflected back into space; the remaining two-thirds is absorbed by the surface, and to some extent by the atmosphere. To balance the absorbed incoming energy, an equal amount of energy must be radiated back to space at longer wavelengths, primarily in the infra-red part of the spectrum. Much of the thermal radiation emitted by land and ocean surfaces is absorbed by the atmosphere, including clouds, and is re-radiated back to Earth. This re-radiation is the so-called "greenhouse effect", acting analogously to the reflective glass walls in a greenhouse. It is the greenhouse gases that absorb and re-radiate a portion of the out-going long-wave radiation back toward the Earth. Although greenhouse gases make up less than 1% of the Earth's atmosphere, global climate is sensitive to even small changes in this concentration. The Earth's natural greenhouse effect thus makes life possible. Human activities have intensified the greenhouse effect that is now triggering global warming (Le Treut et al. 2007).

Greenhouse gases in the atmosphere include water vapor, CO_2, methane (CH_4), nitrous oxide (N_2O), ozone (O_3), and various chlorofluorocarbons, hydrochlorofluorocarbons and aerosols (Bhatti et al. 2006a; IPCC 2007a). These gases may be continuously released into the atmosphere by natural processes such as, decomposition, respiration, volcanic eruptions and ocean outgassing as well as from human activities. The net contribution of each gas to the greenhouse effect depends on the amount released into the atmosphere each year, the length of time it stays in the atmosphere, any indirect effect it has on atmosphere chemistry, and the concentration of other greenhouse gases (Bhatti et al 2006a).

The two most important greenhouse gases are water vapor and CO_2. Water vapor (excluding clouds) causes 36 to 70% of the greenhouse effect while CO_2 causes 9 to 26%. Other greenhouse gases such as CH_4 cause 4 to 9% of the greenhouse effect and $O_{3,}$ 3 to 7% (Kiehl and Trenberth 1999: IPCC 2007a). The two most abundant constituents of the atmosphere, nitrogen and oxygen, cause no greenhouse effect. Clouds exert a blanketing effect similar to that of greenhouse gases, but the effect is offset by their reflectivity since they tend to have a cooling effect. Cloudy nights, however, tend to remain warmer than clear nights. Human activities intensify the blanketing effect. Global concentrations of CO_2, CH_4 and N_2O in the atmosphere have all increased during the industrial era (Fig. 2). Global concentration levels measured in 2005 were: for CO_2 – 379 ppm (parts per million by volume); for CH_4 – 1774 ppb (parts per billion); and for N_2O – 319 ppb (IPCC 2007a).

The amount of CO_2 has increased by about 35% during the industrial era, and has been contributed primarily from the combustion of fossil fuels and deforestation (IPCC 2007a). Deforestation, which is the removal of forest vegetation and replacement by other surface cover, has had a twofold impact on the carbon cycle: the loss of photosynthetic capacity in forest vegetation, and the release of the large carbon stocks that had accumulated in these forest ecosystems over long periods (Apps et al. 2006). Nitrous oxide concentration has also been increasing and is especially contributed from agricultural activities. Methane emissions generated from human activities are primarily the result of activities of livestock, rice cultivation, biomass burning, natural gas delivery systems, landfills and coal mining (Bhatti et al 2006a).

Ozone at the tropospheric level is a secondary air pollutant formed in the atmosphere under bright sunlight from the oxidation of nitrogen oxides and hydrocarbons, and is increasing globally (Percy and Ferrotti 2003). Ozone is considered the most pervasive of air pollutants affecting forests at present and projected into the future. Fowler et al. (1999) have calculated the global forested area at risk to O_3 concentrations >60 ppb will reach 49.8% of the world's forests by 2100, and especially predicted this risk for temperate and sub-polar regions.

Prediction of the future persistence of atmospheric GHGs in the atmosphere is derived from mathematical models that simulate future additions and removals. The predicted concentrations are therefore subject to considerable uncertainties. The increasing concentrations of the various GHGs in the atmosphere during the industrial era provide the dominant factor in radiative forcing of climate. The contribution of each GHG to radiative forcing over a particular time is determined by the change in its concentration in the atmosphere over that period and the effectiveness of the gas in perturbing the radiative balance (IPCC 2007a).

The current concentration of GHGs in the atmosphere is the net result of the history of its past emissions and removals from the atmosphere. These emissions to the atmosphere are offset by chemical and physical processes which, except for CO_2, remove a specific fraction of the amount of gas in the atmosphere each year. The inverse of this removal rate indicates its persistence residency time in the atmosphere. Long-lived GHGs include CO_2, CH_4 and N_2O which are chemically stable and persist in the atmosphere for decades to centuries or longer. Their emission, therefore, has a long-term influence on climate. Carbon dioxide does not have a specific life time residency in the atmosphere because it is continuously cycled between the atmosphere, oceans and land biosphere and its net removal from the atmosphere involves a range of processes with different time scales (IPCC 2007a).

Short-lived GHGs such as sulfur dioxide (SO_2) and carbon monoxide (CO) are chemically reactive and are generally removed by natural oxidative processes in the atmosphere. Ozone in the troposphere is a short-lived GHG and is formed and destroyed by chemical reactions involving other compounds in the atmosphere (IPCC 2007a).

5.0 CLIMATE SCENARIOS FOR ALBERTA IN THE 21st CENTURY

An Alberta Climate Model has been developed that describes average provincial climate conditions for the 30-year period 1961 to 1990 for any geographic location in Alberta. An objective of this Model was “to provide a process for detailed description of Alberta climate, both for current use, and as a baseline from which to estimate impacts of changes suggested for future climates” (Alberta Environment 2005a). The Model was developed from Environment Canada raw monthly climate data for Alberta recording stations, and incorporated four primary climatic variables from which values of 13 climate related variables were derived. These variables have demonstrated or were considered likely to be important in the distribution and responses of trees as well as other organisms to climate (Alberta Environment 2005a).

Using the Alberta Climate Model as a baseline and Global Climate Models, Barrow and Yu (2005) simulated future climate scenarios for Alberta, relative to the baseline period, 1961 – 1990, and projected to the 2020’s, 2050’s, and 2080’s periods. The climate simulations used GHG emission scenarios which are detailed in the Special Report on Emissions Scenarios (SRES; Nakicenovic et al. 2000). Climate change scenarios were developed for minimum, mean and maximum temperatures, precipitation, degree days >5°C (indicative of general plant growth) and annual moisture index, a measure that serves as an indicator of heat and moisture balance for plant growth (Barrow and Yu 2005).

Table 2 shows the predicted changes in annual mean temperatures (AMT), annual mean precipitation (AMP), annual growing degree days (ADD), and annual moisture index (AMI) are summarized for six selected monitored sites. Table 2 also indicates the average expected change for the 2020’s and 2050’s periods.

Table 2. Summary of increases and/or decreases in annual mean temperatures (AMT – °C), precipitation (AMP – mm), mean growing degree days (ADD >5°C), and annual moisture index (AMI) predicted for the 2020's and 2050's period, compared to baseline measurements of 1961-1990.

Location	AMT		AMP		ADD		AMI	
	2020's	2050's	2020's	2050's	2020's	2050's	2020's	2050's
Lethbridge	1.5	3.0	-3.7	-3.2	416.9	830.7	1.0	2.5
Medicine Hat	1.6	3.0	1.7	.9	357.0	664.8	1.0	2.4
Calgary	1.3	2.6	-2.3	6.8	387.8	806.4	0.8	1.8
Edmonton	1.1	2.5	6.0	21.4	338.3	630.6	0.6	1.3
Grande Prairie	0.8	2.1	22.6	35.4	311.8	645.4	0.5	1.2
Fort McMurray	0.9	2.3	33.4	51.9	273.7	470.4	0.4	0.6

[a] Annual moisture index is the ratio of the annual degree day total (with a threshold of 5°C) to the annual precipitation. Adapted from Barrow and Yu (2005).

Future climate scenarios for Alberta are depicted in Figs. 3 to 14 for province-wide annual mean temperature (°C), annual precipitation (mm), degree days >5°C, and annual moisture index for the 2020's and 2050's periods (Barrow and Yu 2005). Annual mean temperature increases by 2050's range between 3° and 5°C, depending upon the mathematical model used. However, data in Table 2 suggest a decreasing trend of temperature increase from south to north in the province for both future periods, relative to the 1961-1990 baseline.

Other reviews of temperature trends in Canada during the 20th century (1900 – 1990 period) show an annual mean temperature increase between 0.5° and 1.5°C in southern parts, with the greatest warming trend occurring in western Canada. Statistically significant increases occur mostly during spring and summer periods. Temperatures from 1950 to 1990 are most distinct in both southern and western Canada, with similar magnitudes of change in minimum and maximum temperatures, and especially evident during winter and spring periods (Bonsal et al. 2001; Zhang et al. 2000).

Annual precipitation trends predicted for the province are generally in the range -10% to +15%, with the largest decreases expected during the summer season. This is also the period when most degree-day units accrue, thus creating a higher risk of moisture stress. A south to north trend of increasing precipitation appears to be evident in Table 2.

Seasonal precipitation trends analyzed for Alberta indicate an average 14% increase during the May to August growing season with the highest increments in the north, northwest and southeastern corner of Alberta (Shen et al. 2003). Across southern Canada, annual precipitation has increased from 5 to 35% during the period 1900 to 1998, with significant negative trends found in southern regions during winter. The data suggest that all parts of Canada have become wetter and warmer during the

1950 to 1998 period (Zhang et al. 2000). Chaikowsky (2000) investigated mean, minimum and maximum temperatures for Alberta, based on 25 climate stations across the province, and used a global climate model to estimate annual trends. Temperature trends were examined over two time periods, 1938-1995 and 1960-1995. The mean temperature increase during the 1938-1995 period was 0.6^{o}C or about 0.1^{o}C/decade and increased by 1.3^{o}C or an average of 0.4^{o}C/decade during the 1960-1995 period. Mean minimum temperatures increased at a similar rate as mean maximum temperatures during the 1960-1995 period. The data showed a cooling trend during July-December, with the greatest cooling occurring in November and the greatest warming trend occurring in March. A similar mean annual increasing trend of about 2^{o}C was shown for the months of February, March and April in Edmonton for the period 1900-1997 (Beaubien and Freeland 2000).

Shen et al. (2003) analysed the long-term (1901-2002) trends in the agroclimate of Alberta. They found no significant long-term trends in start of growing season, end of growing season, or length of growing season. However, there was a trend for earlier date of last spring frost, a later date of first fall frost, and a longer frost-free period. These trends were evident in all provincial agricultural areas.

Growing degree days >5^{o}C and annual moisture index scenarios for Alberta show, respectively, 30 – 50% and 20 -30% increases by the 2020's and 2050's with general decreasing trends from south to north (Table 2) (Barrow and Yu 2005). These trends indicate a lengthening of the growing season in degree days, whereas higher moisture index values generally indicate drier conditions.

Summary of Climate Scenarios for Alberta

- Changes in annual mean temperature expected by the 2050's are 3^o to 5^o. Changes in maximum and minimum temperatures are likely to be similar, except slightly higher for minimum temperatures.
- Annual precipitation trends predicted by the 2050's range between -10% to +15% with the largest decreases expected during the summer season.
- By the 2050's, degree days >5oC are expected to rise by 30%-50%.
- Annual moisture index (AMI) is expected to increase 20% to 30% by the 2050's.
- The expected climate change will result in a longer frost-free growing season, with trends toward earlier date of last spring frost and a later date of first fall frost.
- A cooling trend was detected during July to December with the greatest cooling occurring in November and the greatest warming trend occurring in March.
- Future winters are expected to be warmer with greater precipitation, and spring and summer periods are predicted to be earlier with reduced soil moisture (Sauchyn and Kulshreshtha 2008).
- There is the likelihood of more frequent extreme weather events occurring especially droughts.

6.0 CLIMATE CHANGE EFFECTS ON TREE SPECIES AND DISTRIBUTIONS IN ALBERTA

Climate is the primary force shaping the major biomes of the world (biomes are defined as major biogeographic regions consisting of distinctive plant life such as forests, grasslands, etc.) (Hansen et al. 2001). Mean and variation in annual precipitation and temperature explain much of the observed pattern of biome distribution (Hansen et al. 2001). Climate affects the distribution, growth, productivity and health of trees and forests and has a strong influence on the disturbance regime (Bhatti et al. 2006a). Because of predicted rates of climate change, it is believed that climatic boundaries of biomes will shift northward and to higher elevations, and at rates greater than predicted rates of species migrations (Hansen et al. 2001). Some forests may be limited by nutrient deficiencies. Land-use activities may also affect regional biome and forest distributions through the conversion of natural vegetation to anthropogenic cover types. Climate and land use often interact in ways that can influence forest biodiversity and can jointly influence disturbances such as wildfire, flooding, landslides, etc. (Bhatti et al. 2006a; Hansen et al. 2001).

In several recent studies, tree populations were shown to differ in three climatic optima, and that in a changing climate, populations and their natural geographic range could shift and change differentially (Rehfeldt et al. 1999, 2001, 2002; Rweyongeza et al. 2007b). It has been noted that significant changes in forest ecosystem composition, structure and function are expected to occur at northern latitudes and higher elevations, such as boreal forest ecosystems, where changes in weather related disturbance regimes (e.g., fire, wind, insects, pathogens) and nutrient cycling are primary controls of productivity (IPCC 2001; Gray 2005).

Recent global model simulations indicate that the Earth's climate will warm by an average 1.4 to 5.8°C during the 21st century (IPCC 2001; 2007b). In Alberta, over the period 2000 to 2100, a Global Climate Model estimated a mean warming trend of about 0.3°C per decade, with an overall increase of 5°C (Chaikowsky 2000). Precipitation will also change during the 2000 to 2100 period but its projections are less certain (Barrow and Yu 2005; Shen et al. 2003). These climatic changes along with predicted increases in greenhouse gas (e.g., 2 x CO_2 scenarios) concentrations will undoubtedly affect tree species and their distribution patterns in Alberta during the 21st century. However, evidence as to how northern forests will be affected is somewhat conflicting since forest growth may be stimulated by rising temperatures and CO_2 levels and by longer growing seasons where other factors are not limiting (Hogg et al. 2002).

Considerable evidence already exists that indicate changes in vegetation patterns are occurring. For example, some boreal forest ecosystems in central Alaska were transformed into extensive wetlands during the past few decades of the 20th century (Gray 2005). In addition there is evidence of continued current northward expansion of the range of lodgepole pine in the Yukon (Johnstone and Chapin 2003). In central Alberta, Beaubien and Freeland (2000) and Beaubien and Hall-Beyer (2003) present evidence that spring flowering time during the period 1936 to 2000 has advanced three days for saskatoon (*Amelanchier alnifolia*) and five days for chokecherry (*Prunus virginiana).* During the period 1901 to 1999, Beaubien and Freeland (2000) provided evidence that flowering of trembling aspen has advanced 26 days. Similar advances in flowering dates of 2 to 6 days have also been noted for 18 spring flowering herbaceous plant species typical of deciduous forests in eastern Canada (Houle 2007).

In the prairie provinces, Hogg and Hurdle (1995) used climate moisture index (CMI = mean annual precipitation minus annual potential evapotranspiration) values to overlay on general vegetation zones with incorporated warming of 4-5°C and doubling of CO_2 scenarios in their model. They concluded that about half of the western Canadian boreal forest could be exposed to a drier climate similar to the present Aspen Parkland Zone. Conifers are generally absent in this zone and aspen is restricted to patches of stunted trees interspersed with grassland. If warmer and drier conditions continue as predicted, aspen productivity and other commercial species in the southern boreal forest would be greatly reduced (Figs. 15 and 16). Areas of the Aspen Parkland are shown to increase significantly in the southeastern part of Alberta as well as in the Peace and northern extremes of the province. The Dry Forest Zone is decreased, and the Moist Forest Zone is smaller and more dispersed. These predictions are expected to severely impact the growth, productivity and survival, and hence the distributions of boreal conifer species (e.g., white spruce, black spruce, balsam fir, tamarack, lodgepole pine and jack pine). Trembling aspen, which is the most important deciduous tree in the Canadian boreal forest is also predicted to show reductions in distribution and productivity, and to suffer periodic dieback due mainly to drought and insect defoliation such as by forest tent caterpillar (Hogg et al. 2002; 2005).

Thorpe et al. (2006) examined the suitability of native and some exotic tree species for their current and future adaptation within the prairie provinces. The tree species were first examined using current climate characteristics represented by the 1961-1990 baseline normals for temperature and precipitation, and compared with future climatic scenarios projected to the 2041-2070 period (referred to as the 2050's). The projections were made using global climate models and three bioclimatic variables: growing degree days >5°C, lowest monthly mean temperature (°C), and a moisture index (calculated as the ratio of actual evapotranspiration to potential evapotranspiration). The moisture index expresses the degree to which plant water use is limited by insufficient moisture supply (Thorpe et al. 2006). The results were mapped by comparing the present base (1961-1990) map with the projected future map of the 2050's with the following categories:

- Continued unsuitability (unsuitability in 1961-90 and 2041-70)
- Declining suitability (suitable in 1961-90; unsuitable in 2041-70)
- Continued suitability (suitability in 1961-90 and 2041-70)
- Increased suitability (unsuitability in 1961-90; suitable in 2041-70)

Maps adapted from Thorpe et al. (2006) illustrate projections for the three bioclimatic variables (Figs. 17, 18, 19). Application of the bioclimatic model to the current climate base period gave reasonable approximations to actual distributions for the boreal species currently found in the prairie provinces and included: white spruce, black spruce, balsam fir, jack pine, tamarack, trembling aspen, balsam poplar and paper birch. All of these species showed a northward range shift, consistent with other analyses in the region (e.g. Carr et al. 2004). This shift was mainly driven by the increase in growing degree days. Model output for trembling aspen is shown in Fig. 20 and Manitoba maple in Fig. 21. Model outputs for lodgepole pine, Douglas-fir, ponderosa pine, red pine, Scots pine and Siberian larch are presented in Figs. 22 to 27.

In a similar study of Island Forests of the Great Plains area of the three prairie provinces, the following conclusions were stated for the Cypress Hills (Alberta –Saskatchewan) (Henderson et al. 2002):

- By the 2050's natural regeneration of aspen, lodgepole pine or white spruce is unlikely to be possible except in localized sites. The future landscape is likely to consist of small patches of stressed wooded areas persisting in sheltered sites. By the 2080's regeneration of white spruce and lodgepole pine are likely to be non-existent except in a few sheltered coulees.

- Risk of disturbances is likely to increase (e.g., catastrophic fire, increased vulnerability of lodgepole pine to mountain pine beetle and periodic spruce budworm populations attacking spruce).

Hamann and Wang (2006) studied the potential effects of climate change on ecosystem and tree species distributions in British Columbia. They used an ecosystem-based, climate-envelope modeling approach to describe the realized climate space for British Columbia's ecosystems and to model the realized niche space for tree species under current and projected future climates to the 2025, 2055 and 2085 periods. In their analysis, Hamann and Wang (2006) applied a uniform 2°C increase to all temperature variables and concluded that it had an effect similar to general circulation model predictions of the same magnitude and that the temperature increase appeared to be the main driver of ecosystem shifts. They noted that the largest shifts of climatic envelopes toward the north were observed for the Engelmann spruce –Subalpine fir, Ponderosa pine and Interior Douglas-fir ecosystems. Table 3, extracted from Hamann and Wang (2006) summarizes statistics for changes in distribution and frequency of tree species in British Columbia that are also distributed naturally (except ponderosa pine) in Alberta. In addition, maps are also attached (adapted from Hamann and Wang, 2006) showing projected distribution changes for western larch, white spruce, lodgepole pine, balsam poplar, Douglas-fir, western red cedar, subalpine fir, mountain alder and paper birch (Figs. 28 to 36). These data are provided as an indication of similar scenarios of ecosystem and tree distribution shifts expected to occur in Alberta's forested landscapes. The data also project an anticipated timeline for expected changes to occur as well as the magnitude of change.

Table 3. Changes in tree species distribution and frequency according to ensemble model CCGA1gax for the normal periods 2011-2040 (2025), 2041-2070 (2055), and 2071-2100 (2085).

Tree Species	Model Fit	**Habitat Lost (%)**			**New Habitat (%)**			**Frequency Change (%)**		
		2025	**2055**	**2085**	**2025**	**2055**	**2085**	**2025**	**2055**	**2085**
Abies lasiocarca	87	12	32	54	16	20	19	-24	-50	-75
Alnus tenuifolia	81	13	17	31	25	36	52	-3	-24	-56
Betula papyrifera	83	7	9	5	41	53	66	64	80	62
Larix laricina	85	9	32	68	13	52	75	-4	-28	-65
Larix lyallii	28	84	98	100	58	38	19	-98	-100	-100
Larix occidentalis	54	43	44	61	107	343	508	-17	-20	-49
Picea engelmannii	75	28	32	41	49	80	81	-7	-10	-55
Picea glauca	78	21	40	68	20	17	14	-23	-52	-77
Picea mariana	84	22	43	67	21	21	17	-7	-14	-42
Pinus albicaulis	54	59	70	73	52	73	76	-66	-90	-98
Pinus contorta	88	7	9	27	16	24	31	-13	-24	-50
Pinus flexilis	19	89	100	100	108	381	218	-83	-100	-100
Pinus ponderosa	68	15	6	1	79	311	597	83	179	321
Populus balsamifera	81	10	17	16	30	39	48	1	-8	-1
Populus tremuloides	85	9	12	22	18	25	34	15	-16	-43
Prunus pennsylvanica	59	41	76	97	54	42	17	-44	-78	-98
Prunus virginiana	70	11	3	1	69	126	212	14	55	142
Pseudotsuga menziesii	79	10	11	10	48	82	124	36	76	77

Table Adapted from Hamann and Wang (2006).

Some general trends described for British Columbia that may also be applicable to Alberta (although it is recognized that drought is likely to be a major limiting factor for many tree species in Alberta's forest land base) include:

- Several hardwood species that currently occupy a northern distribution pattern are not likely to decrease in area but are predicted to gain large amounts of new potential habitat;
- Some hardwoods (e.g., balsam poplar and mountain alder) may be relatively unaffected in overall frequency by climate change and may potentially move to higher elevations;
- Some of the most important conifer species (e.g., subalpine fir, white spruce, Engelmann spruce, black spruce, tamarack, and lodgepole pine) are projected to significantly decrease in frequency and/or lose a large portion of their suitable habitat;
- Some species that are generally distributed in the southern portion of British Columbia such as western red cedar, Douglas-fir and ponderosa pine are predicted to gain suitable habitat northward due to migration (similar northward spread potential for Douglas-fir and ponderosa pine were projected for western Alberta by Thorpe et al. (2006)). Rate of migration of forest trees species is expected to be very slow (i.e., <100 km/decade), and will depend upon reproductive age, successful seed production, seed dispersal and germination, as well as on competition factors in establishing in new territories;
- Species that now occur at higher elevation levels such as whitebark pine and alpine larch may lose potential habitat faster than they gain new habitat and are expected to decline in frequency at their current elevations;
- Tree species are not expected to change their distribution or frequency in concert, and differential reproductive rates and dispersal abilities may dictate how individual tree species respond to climate change. The response to climate change is therefore not expected to be uniform throughout different forest ecosystems (Hamann and Wang 2006; Parmasan and Yohe 2003).

Rweyongeza and Yang (2005a, 2005b, 2006), Rweyongeza et al. (2007a, 2007b) examined the genetic variation, growth and survival of major conifer species in Alberta from the results of various field provenance trials. They concluded the following observations that are relevant to future climatic prediction scenarios for the province:

- For white spruce, genetic growth potential declines from central to northern Alberta in response to a decrease in winter temperatures and annual precipitation, and an increase in continentality (January to July temperature differential). Genetic growth potential also declines from medium elevations in central Alberta to higher elevations in the southwest in response to a shorter and cooler growing season (Rweyongeza and Yang 2005c);
- The difference between inhabited and optimum climates is greatest among populations inhabiting climatically harsh environments in northern latitudes or high elevations. This pattern of variation and climatic relationship appears to hold true for white spruce, lodgepole pine and jack pine;
- Northern latitude conifer populations currently inhabiting continental and dry climates and those at higher elevations in the Rocky Mountains currently inhabiting a region with cool and short summers may experience significant growth increases if transferred to central Alberta; the populations currently inhabiting central Alberta will outperform these northern

and southern populations for growth providing that the moisture and thermal environment are optimal, but are more sensitive to climatic transfer to drier and colder environments (Rweyongeza et al. 2007b; Rweyongeza and Yang 2005c);

- Lodgepole pine, which is currently most prevalent at higher elevations where precipitation is high but growing seasons are cool and short, would attain maximum height growth east and at lower elevations than its current range where winters are cooler, summers are longer and warmer and precipitation is lower. Conversely, jack pine which occurs at lower elevations to the east where summers are warmer and drier, would attain better height growth to the west and at higher elevations where summers are cooler and precipitation is higher than in its currently occupied range. The hybrids of the two parental species currently occupy an area of climate intermediate to that of their parents which is optimal for all three taxa (Rweyongeza et al. 2007a; Rweyongeza et al. 2007b).
- Drought stress caused by increased temperatures and declines in precipitation is predicted to be the main cause of decline in conifer productivity predicted to the 2030's. Large declines in growth and survival are predicted for northern and central Alberta, where as growth and survival could be increased significantly at higher elevation areas in south western Alberta due to high annual precipitation and increased growing degree days;
- Balsam fir in Alberta is likely to be a declining species under climate change scenarios because it is considered to have a low tolerance to fire, is vulnerable to spruce budworm injury, is susceptible to diseases, and has high moisture requirements (Rweyongeza et al. 2007b; Volney and Hirsch 2005);
- Climatic warming that intensifies the risk of drought will adversely affect northern Alberta since this region already experiences drought, and large losses in productivity are predicted (Hogg et al., 2002, 2005; Rweyongeza et al. 2007a).

Summary of Predictions of Tree Species and Distributions for Alberta

- Climate changes projected beyond the 2020's for the prairie provinces indicate temperature increases that are greater than elsewhere in southern Canada (Sauchyn and Kulshreshtha 2008). Consequently, it is concluded that the most significant threat posed by climate change is the projected increase in climate variability and frequency of extreme events, especially drought. Increases in water scarcity represent the most serious climate risk and will impact tree growth, survival, productivity and distribution. Impacts will be most visible in isolated island forests and forest fringe areas, and especially at the southern boundary of the boreal forest (Sauchyn and Kulshreshtha 2008).
- Climate model predictions indicate that about half of the western Canadian boreal forest could be exposed to a drier climate similar to the present Aspen Parkland Zone areas of the Parkland Region. Drier areas are predicted to increase in the southeastern part of Alberta as well as in areas in the Peace and extreme northern parts of the province (Figs. 15 and 16). Drier conditions are also forecast for much of the central to northern boreal forest areas (Fig. 16). These changes, expected by the 2050's, will cause reductions in the distribution and productivity of trembling aspen, with periodic dieback due mainly to drought and insect defoliations (Figs. 20, 21).
- Tree species ranges at higher elevations in Alberta are limited by thermal environments, and these species may move to higher elevations with increasing temperatures. This could include subalpine fir, Engelmann spruce, alpine larch, Interior Douglas-fir, whitebark pine, balsam poplar, lodgepole pine, white spruce and aspen.

- Tree species in the Dry Mixedwood, Parkland and Montane subregions are likely to be limited by drought, and include trembling aspen, balsam poplar, lodgepole pine, white spruce, black spruce, tamarack and paper birch.
- Both in British Columbia and Alberta, some of the most important conifer species (e.g., white spruce, black spruce, tamarack, lodgepole pine and balsam fir) are expected to lose a portion of their current suitable habitat (Figs. 22, 28, 32 and 33).
- Balsam fir may be particularly vulnerable under climate change scenarios.
- Some tree species such as western larch, Douglas-fir, ponderosa pine, Scots pine and Siberian larch are likely to gain new habitat suitable for their growth and survival in western Alberta by the 2050's (see Figs. 23, 24, 26, 27, 31 and 35).
- For white spruce, genetic growth potential declines from central to northern Alberta in response to a decrease in winter temperatures and annual precipitation, and to an increase in continentality (i.e., January and July temperature differential). Genetic growth potential also declines from medium to higher elevations in central Alberta in response to a shorter and cooler growing season (Rweyongeza et al. 2007b).
- Lodgepole pine, which is currently most prevalent at higher elevations where precipitation is high but growing seasons are cool and short, has the potential to attain maximum height growth eastward and at lower elevations than its current range where winters are cooler, summers are longer and warmer and precipitation is lower (Rweyongeza et al. 2007a; Rweyongeza et al. 2007b).
- Jack pine, conversely to that of lodgepole pine, occurs at lower elevations eastward where summers are warmer and drier, and would attain better height growth to the west and at higher elevations where summers are cooler but precipitation is higher than in the currently occupied range. The hybrids of the two parental species currently occupy an area of climate intermediate to that of their parents which is optimal for all three taxa (Rweyongeza et al. 2007a).
- Factors other than temperature and drought will influence tree species distributions, growth and survival in Alberta and include other disturbance events (fire, insects, pathogens, freeze-thaw, storms, topography, species competition, forest fragmentation, harvesting, and possibly CO_2 fertilization (Sauchyn and Kulshreshtha 2008).

7.0 CLIMATE CHANGE IMPACTS ON WETLANDS AND PEATLANDS

Globally, the Boreal Forest stores about 22% of the total carbon on the Earth's land surface. This is largely because of the climate in boreal regions where colder temperatures reduce decomposition rates, allowing deep organic layers to develop over centuries (IBCC 2007). In Canada, the Boreal Forest stores an estimated 186 billion tons of carbon in forest and peatland ecosystems. About 30% of the Canadian Boreal is covered by wetlands, which include marshes, fens, bogs, swamps and peatlands. Wetlands are an interface between the terrestrial and aquatic environments and their development and ecological viability depend on water saturation for at least part of the year. Wetlands are sensitive to changes in hydrology as temperature, precipitation, surface runoff, snow cover, length of freezing season, permafrost, ground water storage and evapotranspiration are altered due to climate change. Predicted warmer temperatures, shorter warmer winters, and longer summers will enhance evaporative losses and reduce water levels in wetland areas over time (Mortsch 2006). Protecting these efficient carbon storage ecosystems is therefore critical and necessary to help reduce global warming.

In Alberta, about 18% of the land base is covered by wetlands, of which about 90% is classed as peatlands (Vitt et al. 1996), distributed generally throughout the northern half of the province (Schneider 2002). Peatlands are most abundant in the Boreal Forest Region where they occur as extensive wooded areas, permafrost bog areas in the north and in upland areas, and as non-permafrost bogs to the south. Peatlands in Alberta may contain as much as 70% of the provinces soil carbon. The distribution and type of wetlands found in Alberta are controlled largely by climate and geologic factors, of which mean annual temperatures and thermal seasonal aridity index or TSAI (defined as the total annual precipitation divided by mean growing season temperature) are important (Vitt et al. 1996). Peat is formed when decaying plant materials – mosses, sedges, grasses, shrubs and trees – accumulate in permanently water-logged conditions. If left undisturbed, peatlands can potentially store the carbon sequestered in these plant materials for thousands of years (IBCC 2007). Non-peat accumulating wetlands dominate in the Parkland and Grassland regions in Alberta. Besides serving as large carbon storage reservoirs, peatlands provide habitat for many plant and animal species, retain, purify and deliver fresh water, provide flood and storm water control, water filtration, absorb pollutants, provide groundwater replenishment and provide aesthetics, recreational and educational values (IBCC 2007, Wilson et al. 2001). Peatlands are important net sinks of carbon because their rates of plant production are greater than their rates of organic matter decomposition (Mortsch 2006).

Approximately the northern quarter of the land base in Alberta includes two areas: one is categorized as having isolated patches of permafrost, and the other area has sporadic areas of permafrost. Farther north in the Yukon and Northwest Territories, the permafrost zone becomes more continuous (IBCC 2007). Permafrost is defined as permanently frozen soil, sediment or rock that remains at or below 0°C for at least two years. Carbon is stored under the frozen ground through a slow freeze-thaw process that progressively moves organic matter deeper into the ground where it is sealed off from decomposition by the cold temperature. The thawing of permafrost increases the rate of decomposition of organic matter contained in it, resulting in a release of carbon into the atmosphere (IBCC 2007).

Important controls on the carbon budget of peatlands include plant communities, peat quality, temperature, and hydrology, especially the position of the water table. Anaerobic conditions usually develop in a peat profile due to waterlogged conditions and high water levels, and warm temperatures stimulate the production of methane. Emissions of CO_2 increase under dry aerobic conditions. Climate change, therefore is expected to affect these controls and influence the role of wetlands as sinks (Mortsch 2006). Studies also suggest that peatlands in areas of continuous permafrost may become net sources of CO_2 to the atmosphere due to climate warming (Mortsch 2006). The lower water table projected to occur with climate change suggests that most peatland areas will likely have decreased methane emissions. However, methane emissions are expected to decrease in southern regions but increase in northern regions due to warmer temperatures, longer growing season, and permafrost soil collapse features. Climate change will also likely increase net productivity and cause increases in CO_2 emissions from lowered water table and warmer temperatures, thus decreasing the total carbon storage. It is predicted that many peatland areas may become sources of carbon, rather than sinks (Mortsch 2006).

In summary, climate change is likely to have the following impacts on wetlands/peatlands (Mortsch 2006; Vitt 2006):

- Wetland/peatland ecosystems will shift northward;
- There will be lowered water table with enhanced decomposition;
- Reduction of net primary production of the ground layer and reduced carbon input to the ecosystem;
- Some below ground net primary production may increase in some peatland types and methane production may increase;
- Rates of microbial respiration will increase, releasing increased carbon to the atmosphere;
- Residence time of peat in aerobic conditions will increase and cause increased CO2 releases to the atmosphere;
- Continued aridity will limit the presence of some bog species and cause some peatlands to decrease in area, or be put at risk due to increased decomposition;
- Altered disturbance regimes, especially increases in fire frequency may lead to catastrophic carbon losses from peatlands, especially bogs;
- Wetlands appear to be particularly favourable habitats for invasive species, and warmer temperatures may compound the problem by allowing more species to survive the winter period than would otherwise survive under more severe climatic conditions (Warner and Asada 2006);
- It may be speculated that the climatic impacts predicted for wetlands/peatlands will result in habitat changes that will cause shifts in tree species distributions; i.e., black spruce-tamarack habitats may be reduced or replaced and become favourable habitats for white spruce, birch, aspen and poplar species.

8.0 CLIMATE CHANGE IMPACTS ON FOREST ECOSYSTEMS AND BIODIVERSITY

Forest ecosystems are predicted to change significantly over the next decades of the 21st century in response to pressures from land-use changes and from a changing climate. Rising temperatures and GHG concentrations will continue to affect moisture and nutrient regimes, wind patterns, and the frequency of disturbance events. These changes will impact terrestrial ecosystems and their constituent organisms in a variety of ways, some of which will be negative and some positive. The most significant changes in ecosystem composition, structure and function are expected to occur at northern latitudes and higher altitudes such as boreal forest ecosystems, where changes in weather-related disturbance regimes and nutrient cycling are primary controls on productivity (IPCC 2001; Malcolm et al. 2002).

By definition, an ecosystem includes organisms of species with genetic diversity that live and die within their ecosystem. Ecosystems are recognizable as occupying specific areas of Earth space, and in which there is a flow of energy and transformation of matter in space-in-time. Within each ecosystem there is a network of organisms, atmosphere, rock, soil and water, all interacting with each other and with other ecosystems. Each ecosystem is therefore distinctive in having its own composition (i.e., species diversity), structure (i.e., chemical and physical organization) and function (i.e., flow and transfer of energy and creation and dissolution of matter) characteristics (Gray 2005).

Forest ecosystems are highly complex and therefore the effects of climate change on them and the ways they may respond are difficult to predict, since many variables, different organisms and their interactions all need to be considered. A number of climate aspects relevant to forests and forestry are likely to change due to global warming and include the length of the vegetative period, water availability, soil temperature and snow conditions (Bergh et al. 2004; Shaver et al. 2000). Some major ecosystem functions are likely to be disrupted such as biomass production, biogeochemical cycling, soil and water relationships, animal-plant interactions, and species diversity (Graham et al. 1990; IPCC 2001).

All ecological systems are dynamic, and variations in climate, disturbance, and other ecological processes are required for maintaining some species and communities. However, rates of change in biodiversity are likely to accelerate substantially by human land-use and climate changes (Hansen et al. 2000). Projections of global warming effects on ecosystems by the use of global climate models may tell little about how temperatures will change in a particular location or how the ecosystems in that location will respond. Some of the problems with predictive models are that they may not incorporate both direct and indirect effects of warming (Shaver et al. 2000), or fail to take into account the non-linearity (i.e., interactions among components of a system are not directly proportional) of many ecological processes (Burkett et al. 2005). The impact of CO_2 concentrations on ecosystems have a generally direct influence that is limited almost entirely to leaves (photosynthesis, stomatal opening, and perhaps respiration), whereas rising temperature effects on ecosystems are more complex because temperature directly impacts virtually all chemical and biological processes. Indirect effects in ecosystems result from interactions among processes affected directly by environmental change. Such interactions may lead to feedbacks that can be both positive and negative (Shaver et al. 2000). This implies that the responses to temperature change and CO_2 will likely vary among ecosystems in magnitude and direction.

Forest ecosystem responses occur at different scales (Graham et al. 1990): for example, processes that involve exchanges of water, heat and CO_2 at the leaf/needle surface have response times in seconds or days; forest growth and community composition have intermediate response times of decades to centuries; and geographical distribution of forests have long-term response of centuries to millennia. All of these responses can be altered by human intervention.

Graham et al. (1990) describe several ecological phenomena that strongly influence the composition, structure and function of forest ecosystems. These include: (1) competition and succession, (2) water use, (3) nutrient cycling, (4) disturbance regimes, and (5) productivity.

(1) Competition and succession: Because of elevated levels of CO_2 concentration and global warming, successional paths may change and new community types may evolve. The rate at which communities will change is difficult to predict, because it depends not only on competitive differences but also on species longevity, changes in disturbance patterns, and seed source availability.

(2) Water use: Water use will vary with different ecosystems. The efficient use of water generally increases with higher concentrations of CO_2 (especially seedlings) and may depend on many factors. For example, leaf area is positively correlated with stand water use and to evaporative demand (i.e., increases with higher temperatures). Water use is also a function of precipitation and the timing of precipitation. A deep and dense forest canopy is poorly coupled with the atmosphere so that water use will be largely a function of net radiation absorbed by the canopy, rather than of canopy conductance.

(3) Nutrient cycling: Climate change will alter litter decomposition rates, plant nutrient uptake and/or internal cycling. Decomposition rates will change in response to alterations in the physical environment, litter quality, quantity and abundance, and to the types of decomposers. A warmer climate may increase the rate of decomposition by enhancing fungal and bacterial growth, whereas a drier climate may have the opposite effect. Activity levels of forest soil arthropods will change. Higher concentrations of CO_2 can change the C:N ratio found in plant tissue, which will also show up in the litter, and thereby have an effect on decomposers. However, lignin:N ratios tend to remain the same or decrease under increased CO_2 concentrations.

(4) Disturbance regimes: Interaction between disturbance regimes and climate change can rapidly alter forest structure and contribute to species shifts in distribution as well as local extinctions. Increased frequency of dry years may lead to increased fire frequency and to drought conditions. Fire conditions respond to fuel moisture, which depends upon precipitation and relative humidity. Fires tend to be clustered during low effective precipitation and soil moisture. Climate change may increase the incidence of insect or disease outbreaks, or allow new pest conditions, increase host tree stress and vulnerability by lowering their resistance to pests. Disturbance regimes may also enhance conditions for competitiveness of weedy invasive plant species.

(5) Productivity (in terms of wood production): Site specific ecosystem productivity will change in response to different factors (e.g., species composition, temperature/moisture conditions, and CO_2 fertilization effects). Responses to CO_2 concentrations for above ground and below ground growth are complex and variable. Productivity may decrease initially, and increase later so that the short-term and long-term responses could be different. Productivity will be a function of responses of trees and their inherent growth patterns. Young forests may respond differently than older forests. Productivity may not increase if there is no carbon sink to absorb the extra photosynthate; i.e., the ecosystem must be environmentally capable of increasing its biomass.

Physiological processes within trees that may be influenced include phenology, life-cycle events such as reproduction and death, photosysnthesis, transpiration, respiration, carbon allocation, nutrient uptake, and nutrient allocation.

There is considerable interest and a large literature developed to model the response of ecosystems to climate and global changes; many of these models focus on ecosystem composition, structure and function at global and regional scales (IPCC 2001). One important reason for doing so is to estimate carbon fluxes and their contribution to the global carbon cycle (Apps et al. 2006; IPCC 2001). This involves making estimates of net primary productivity (NPP), net ecosystem productivity (NEP), and net biome productivity (NBP). Plants are responsible for most of the carbon uptake by terrestrial ecosystems. Most of this carbon is returned to the atmosphere via a series of processes including respiration, consumption, combustion, and chemical oxidation (IPCC 2001). Gross primary productivity (GPP) of an ecosystem is the total uptake through photosysnthesis, whereas NPP is the rate of accumulation of carbon after losses from plant respiration and other metabolic processes. Consumption of plant material by animals, fungi, and bacteria returns carbon to the atmosphere, and the rate of accumulation of carbon over a whole ecosystem and over a whole season or other time period is referred to as net ecosystem production or NEP. In a given ecosystem, NEP is positive in many years and carbon accumulates. Major disturbances such as fires, insects and other extreme events that cause death of trees and other organisms release greater than usual amounts of carbon. The average accumulation of carbon over large areas and/or long periods is called net biome productivity or NBP (IPCC 2001).

There are two paradigms that describe the way ecosystems respond to global change (IPCC 2001). The first, "ecosystem movement paradigm" assumes that ecosystems will migrate relatively intact to new locations that are close analogs to their current climate and environment. However, this paradigm is an over simplification of what actually will happen, and it is unlikely because of different climatic responses of species, intra-species genetic variability, different longevities, different migration abilities, and effects of invading species (IPCC 2001; Natural Resources Canada 2004).

The alternative paradigm, "ecosystem modification paradigm" assumes that as climate and the environmental factors change, there will be in situ changes in species competition and dominance. Changes will occur because some species decline in abundance or become locally extinct, while others increase in abundance. The longevity of individuals, the age structure of existing populations, and the arrival of invading species will modify these changes. The outcome may be ecosystem types that are different from those present initially. Application of this paradigm has been difficult for practical forecasting (IPCC 2001).

Although there is no single definition of biodiversity, it refers to the variety of life forms including plants, animals and microorganisms, the genes they contain and the ecosystems they form as well as the life processes that support them. These life forms are products of thousands or millions of years of evolutionary history (Biodiversity Unit 1993).

Biodiversity is usually considered at three levels: genetic diversity, species diversity and ecosystem diversity. Genetic diversity refers to the variation of genes within a species. This covers genetic variation between distinct populations of the same species as well as variation within a population. Species diversity refers to the variety of species which can be categorized by species richness, species abundance and by taxonomic or phylogenetic diversity. Species richness may be measured by counting the number of species in a defined area. A measure of species abundance can be obtained by sampling the numbers among species. A measure of taxonomic diversity considers the genetic relationships between different groups of species. Ecosystem diversity is more difficult to define but encompasses the broad differences between ecosystem types and the diversity of habitats and ecological processes occurring within each ecosystem type (Biodiversity Unit 1993).

Biological diversity is important because humanity depends upon it for their sustenance, health, well being and enjoyment of life on fundamental biological systems and processes. Humanity derives all of its food, many medicines and industrial products from the wild and domesticated components of biological diversity (Biodiversity Unit 1993). Biodiversity is also a critical element for the sustainability of forest ecosystems (Volney and Hirsch 2005).

The benefits of maintaining biodiversity have been estimated to be 100 times greater than the costs. As an example, insects, birds and bats pollinate crops, parasitoid and predatory species control pest populations, wetlands act as giant sponges to control flooding and to provide clean water, plants moderate climate and create habitat and provide food for species used by humans, and bacteria break down dead organic matter and generate soil. In addition, the oxygen in the air we breathe is maintained by photosynthesizing plants. Most prescription drugs used in North America are derived from plants, fungi and bacteria. Spiritual, recreational and cultural benefits are also obtained from places where biodiversity remains relatively intact (Biodiversity and Forest Management in BC 2005).

Habitat loss and forest fragmentation are recognized as the main causes of species extinctions and loss of forest biodiversity. Disturbances, both natural (e.g., fire, insects, pathogens, wind, etc.) or human-caused (e.g., harvesting, land-use changes, etc.) all contribute to the loss of habitat and forest fragmentation. When forests are fragmented, habitat is lost and the spatial arrangement of habitat is changed. However, the impacts of biodiversity could be both positive (i.e., increases in abundance of some species) and negative (i.e., loss of gene flow due to barriers to movement, loss of species and individuals, crowding, increased competition, and degredation of habitat due to edge effects and species invasions). Fragmentation may degrade habitat for some species while improving it for others. Most current evidence suggests that the overall habitat loss has a much larger effect on biodiversity than the spatial arrangement of remnant habitat (Biodiversity and Forest Management in BC 2005).

Overall biodiversity of ecosystems is forecast to decrease (though some may actually increase) in the future as a result of a multitude of pressures that include land-use intensity and associated destruction of habitats and habitat fragmentation, introduction of exotic and invasive species, and direct effects on reproduction, dominance, and survival. Some of these changes may take place independent of climate change.

Summary of Impacts on Forest Ecosystems and Biodiversity Predictions for Alberta

- Forest ecosystems will change in response to the changing climate and in response to pressures from human land-use changes;
- The greatest magnitude of changes will likely occur in northern latitudes (e.g., Boreal Forest) and at higher altitudes;
- Expected changes include a lengthening of the vegetative period, reduced water availability, and increased soil temperatures;
- Ecosystem functions such as biomass production, biochemical cycling, soil-water relations, animal-plant interactions and species diversity will be disrupted or changed;
- Rates of changes in biodiversity are likely to accelerate;
- Responses to temperature change and increased CO_2 concentrations will likely vary among ecosystems in magnitude and direction;
- Main factors that will strongly influence the composition, structure and function of forest ecosystems include competition and succession, water use, nutrient cycling, disturbance regimes and productivity;
- Forest ecosystems will be changed and modified in predictable and unpredictable ways because some species will decline in abundance or become locally extinct, while others may increase in abundance. The outcome may be ecosystem types that are different from those at present;
- Deforestation, habitat loss and forest fragmentation are likely to be the main causes of species extinctions and reduced biodiversity;
- Predicted increases in forest disturbances (e.g., fire, insects, pathogens, wind, harvesting, land-use changes, etc.) will contribute to the loss of habitat and forest fragmentation;
- Impacts of climate change on forest biodiversity could be both positive and negative;
- Overall biodiversity of ecosystems is predicted to decrease.

9.0 CLIMATE CHANGE EFFECTS ON FOREST PRODUCTIVITY

A major science issue of global warming is the potential impact of climate change on forest growth and primary production. On the positive side are increased length of growing season, increased soil and air temperatures and nutrient cycling as well as the possibility of greater N deposition and CO_2 fertilization effects; while on the negative side are increased incidence of extreme events (forest disturbances), drought, reduced seasonal moisture availability and air quality impacts such as O_3. Positive effects could lead to greater forest productivity and increased carbon sequestration. The negative effects may impair or cancel forest production increases. Western Canadian interior forests are viewed as potentially more vulnerable to climate change impacts than are eastern forests, especially because of the higher variability of climate and increased drought risks predicted for the southern boreal and parkland areas. (Hogg and Bernier 2005; Sauchyn and Kulshreshtha 2008; Sauchyn et al. 2008).

Forest productivity is determined by a number of environmental factors affected by climate change and include temperature, moisture availability, nutrient availability, and atmospheric CO_2 concentration. In general, the increase in temperatures is expected to rise faster at night than during the day, and that winter temperatures will increase faster than summer temperatures (Johnston 2003). These changes will result in more frost-free days and a lengthening of the growing season, and warmer soil temperatures, all of which will influence growing conditions. Higher winter temperatures and early bud break conditions, however, carry risks of decreasing frost hardening of trees and increased risks of shoot damages and tree dieback. These conditions also favor more frequent late-spring frosts and frost-heaving of seedlings (Colombo 1998; Natural Resources Canada 2004). For example, an increase in summer temperature of 3 – 4°C is predicted to result in bud break of white spruce occurring 2 to 4 weeks earlier than present (Colombo 1998).

Boisvenue and Running (2006) reviewed documented evidence in the scientific literature of the impacts of climate change trends on forest productivity since the 1950's. In North America, satellite imagery studies detected a 2 – 8% increase in net primary productivity between 1982 and 1998. This increase was thought to have resulted from increased precipitation and humidity, and an increase in air temperatures. Other documented evidence has pointed to increases in productivity in boreal forests as well as some decreases.

In northern forest-tundra sites in Quebec, increases in height growth and leader shoot elongation of black spruce were reported, whereas suppressed height growth appeared to be more prominent in southern parts of the forest-tundra areas. Similar observations of increased growth were noted on conifer species in the northern reaches of trees in taiga forests of northern Europe.

Most studies in northern Europe show an increase in conifer growth productivity. Long-term yield experiments in Sweden, for example, indicate that site productivity has increased in most parts of the country during the past 30 – 40 years. Similar reports of increases were noted for Finland, France, Austria, Switzerland and Russia. While few studies were sited showing increased productivity in the United States and Canada, the authors concluded that there is a general increasing trend observed in net primary productivity for boreal temperate forests across North America, northern Europe, some parts of southern Europe and Japan. Productivity increases are projected to be generally larger in European forests than in North American forests. In Europe as a whole, forest growth trends are positive, except in some sites where extreme growth limitations persist as a result of increased temperatures and a water deficit. Increases in net ecosystem productivity of high elevation temperate conifer forests of central Europe were attributed to increased nitrogen atmospheric deposition and to the fertilization effect of increased CO_2 concentrations for conifer forests at mid- and low elevations (Boisvenue and Running 2006). These observations of increased productivity are in agreement with the small net primary productivity increases (2 – 8%) detected from satellite-based analyses.

Johnston and Williamson (2005) site several factors that will influence overall forest productivity, such as higher CO_2 concentrations that provide a "fertilizer" effect as well as an enhancement of efficient water use in some plants. There may also be an increase in frequency and intensity of drought periods, variable responses of tree species to changing environmental conditions and tree growth responses to the various forest disturbances. They suggest that these factors will likely lead to changes in forest structure and productivity, and ultimately change how forests will be managed.

Johnston and Williamson (2005) investigated climate-related factors that will influence the future growth and yield of white spruce ecosystems in central Saskatchewan and applied a forest ecosystem model to project impacts of climate change on future forest productivity to the 2080's. Under most future scenarios examined, white spruce net primary productivity increased, but declined during extreme drought. They cautioned, however, that realization of potential productivity increases may depend on the ability to reforest sites optimally, and that some non-climatic factors such as nitrogen availability may inhibit productivity gains. In contrast, predicted changes in Alberta's climate (e.g., increasing temperature and low annual moisture index) suggest that growth and survival of white spruce will be seriously reduced in the central and northern parts of the province, and that these changes could come as early as 2030-2039 (Rweyongeza et al. 2007b).

Studies of white spruce tree growth in Alaska suggest that growth has been declining due to temperature-moisture related stress (Soja et al. 2007). Drought stress likely was also the main contributing factor along with stand age and stand history accounting for the decline of stands of Alaska birch (*Betula neoalaskana*) in southwestern Alaska (Ott and Mahal 2007).

In the foothills region of Alberta, site indices and productivity of lodgepole pine have been examined in post-harvest stand development and compared with site indices in their predecessor fire-origin stands. This examination of growth and yield showed that there has been an average increase in site index in the post-harvest stands of about 23% or 3.5m. The increase, however, was not uniform at all sites but was most prominent on sites classed as "poor" (up to 60% increase in site index), and showed little or no site index increase on sites classed as "rich". It was suggested that the post-harvest increased productivity was likely attributed to several factors including improved forest management practices (e.g., site preparation and lower stand density), increased nitrogen deposition, increased CO_2 concentrations, increased warming trend and/or lengthening of the growing season (Dempster 2003, 2004; Huang et al. 2004; Logan and Price 2004;).

A recent study examined the survival, growth and productivity of planted lodgepole pine, jack pine and their hybrids in provenance trials across Alberta to determine their responses to different climatic variables. The studies (Rweyongeza et al. 2007a) confirmed that lodgepole and jack pine are often occupying sub-optimal climatic environments for growth. This demonstrates that climatic transfer of these two species to plantations located in areas of more optimal climate could increase productivity through realizing more of their genetic growth potential. Predicting optimal growing conditions, however, becomes complicated when attempts are made to incorporate trends in predicted future climates. These studies support the views expressed in other studies of selecting response functions for lodgepole pine populations for future climates (Rehfeldt et al.1999, 2001; Wang et al. 2006). As climate becomes warmer and drier during the 21st century, it is predicted that there will be substantial declines in survival, growth and productivity of lodgepole pine at many locations away from the Rocky Mountain eastern slopes (Yang et al. 2007).

In a comparative study of site indices of plantation-grown lodgepole pine in Canada and Scandinavia, temperature regime was shown to have a strong influence on productivity and that the length of the growing season is more important than the maximum temperature in Scandinavia. Productivity of provenances in Canada (mostly originating from British Columbia and the Yukon) suggested that there was a stronger influence of other factors and the length of the growing season was less important (Fries et al. 2000).

Monserud et al. (2006) examined the relationship between climate and lodgepole pine site productivity in Alberta and developed spatial maps depicting site indices and site productivity across the province. In their analysis, the strongest climatic predictors of site index were all measures of heat: e.g., the Julian date when growing degree days above 5°C reaches 100, and July mean temperature. A similar study of site index values of lodgepole pine in Canada and Scandinavia also reported that temperature variables were strongly correlated with site index (Fries et al. 1998, 2000). Although precipitation and winter temperature were not correlated with lodgepole pine site index in Alberta, the study did not imply that these factors were unimportant, but that they were not currently limiting within the range of this species (Monserud and Huang 2003; Monserud et al. 2006). The authors concluded that climate is an important component of site productivity and accounts for 24 to 27% of the variation in site index across the province.

Site index is a species-specific measure of the potential productivity of a site and is most often defined as the height of a site tree at breast height age 50 (Nigh et al. 2004; Stearns-Smith 2001). Site indices developed for a species provide short- and long-term predictive information on expected productivity and are therefore considered as relatively constant values. An important concern with climate change effects, however, is whether and in which direction site indices will change over time in response to rising temperatures and increased concentrations of GHGs.

Nigh et al. (2004) examined the impact of climate change on site productivity for lodgepole pine, spruce and Douglas-fir in British Columbia and developed models that relate site index to the climate attributes. The models allow predictions of the climatic conditions on a site and to estimate the impact of climate on site index. The study found that site index was positively related to temperature and moisture, and they predicted that stand productivity of all three tree species would likely increase under future climatic warming. Use of the models operate on the premise that the temporal pattern of a site productivity-climate correlation can be predicted from its spatial pattern, as shown earlier to be highly effective for lodgepole pine (Rehfeldt et al. 1999).

From selected climate change scenarios, the models of Nigh et al. (2004) could be used to evaluate the impact of these scenarios on site productivity. The statistical model can also serve as a valuable tool to guide reforestation programs by matching the species to the site and climate according to the direction and magnitude of climate change.

In a Canadian prairies-wide study of factors affecting the growth and dieback of aspen forests Hogg et al. (2005) established a network of research plots in 72 aspen stands in 2000. The study, entitled "Climate Change Impacts on Productivity and Health of Aspen" or CIPHA, was established to conduct annual monitoring of tree growth and health with a focus on relatively pure 40 to 80 year old stands. The main objective was to analyze tree-ring data to examine the cause and magnitude of aspen growth patterns over the period 1951 to 2000. The results of the study indicated that large oscillations in aspen growth were evident on a region-wide scale and appeared to be representative of a wide range of stand ages and composition, including the aspen component of mixedwood stands (Hogg and Schwarz 1999).

From the analyses of tree-ring data, the study found that aspen tree growth during the 50-year period was more affected by interannual variation in moisture and insect defoliation than temperature. At a regional scale, cumulative growing degree days from April 1 to July 31, were a significant factor, but only secondarily. Drought and insect defoliation events both operate across large spatial areas and their combined impacts resulted in regionally averaged growth reductions of up to 50% across a large portion of the three prairie provinces. The study pointed out the need to incorporate climatic variation and insect defoliation in stand-based models of aspen growth and yield. While insect defoliation was a major factor affecting year-to-year variation, moisture was the most important factor limiting the stem growth and above-ground biomass (Hogg et al. 2005). Other studies from southwestern Alberta have also shown positive relationships between radial growth and precipitation in limber pine (Case and MacDonald 1995) and in Douglas-fir (Watson and Luckman 2002).

Several studies of aspen growth in western Canada to date all suggest that drought is the most important climatic factor causing reduced stem growth, top dieback and mortality throughout the aspen forests distributed mainly in the more southerly portions of the boreal and parkland zones (Barr et al. 2006; Frey et al. 2004; Hogg and Hurdle 1995; Hogg and Wein 2005; Hogg et al. 2002, 2005). In addition to drought, other factors that will add constraints on growth and distribution of aspen forests include disturbances such as fire, insects (especially defoliators), diseases, wind storms and freeze-thaw events during winter and spring (Hogg and Bernier 2005). Future frequency and extent of these events will likely have a major impact on aspen, spruce-aspen, and other boreal tree species. These events will ultimately influence changes in tree distributions, growth, productivity, age-class distributions and regeneration (Hogg and Bernier 2005; Hogg and Wein 2005; Hogg et al. 2007).

Plantations of hybrid poplars (*Populus* spp.) have been established in north-central Alberta in recent years as a source of pulp (Welham et al. 2007), and have been widely planted in farm shelterbelts. Areas planted for forestry use are likely to increase in the future because of their rapid growth potential, the increasing remoteness of native stands from mills and markets, pressures to protect native forests, and afforestation opportunities to enhance carbon sequestration (Volney et al. 2007). Using an ecosystem management model, Welham et al. (2007) examined the long-term productivity of hybrid poplar plantations in Saskatchewan over a 100 year horizon composed of five 20-year rotations. The productivity simulations indicated that leaching losses of soil nitrogen during successive harvests contributed to a long-term decline in stemwood productivity. The model did not take into account increasing risks of drought tolerance and uncertainties associated with insect and disease agents, which can carry a high probability of impact (Volney et al. 2007). While growth potential of hybrid poplar clones will likely benefit from the projected increased CO_2 concentrations and a longer growing season by producing increased height growth, dry mass and basal area, the exposure of trees to tropospheric levels of O_3 can potentially negate any growth and productivity enhancements (Dickson et al. 1998). Data presented by Dickson et al. (1998) indicated that hybrid poplar genotypes that grew most rapidly also showed the greatest negative response to O_3 exposure. Although important traits in hybrid poplar selection will always be selected for, it is likely that future planting stock will require increased genetic selection for drought tolerance, insect and disease resistance, as well as for growth and productivity (Dickson et al. 1998).

Summary of Climate Change Effects on Forest Productivity Predicted for Alberta

- Potential impacts of climate change on forest growth and productivity will be positive in many situations (due to lengthening of the growing season, increased soil and air temperatures and nutrient cycling, more frost-free days, greater nitrogen deposition and CO_2 fertilization effects) and negative in other situations (due to increased disturbance events, drought, reduced moisture availability and air quality impacts such as O_3);
- Positive effects could lead to increased carbon sequestration;
- Western forests in Canada are viewed as more vulnerable to climate change impacts than are eastern forests, especially because of higher variability of climate and the increased drought risks (Sauchyn and Kulshreshtha 2008; Sauchyn et al. 2008);
- Higher winter and spring temperatures may change the seasonal phenological development of tree species and increase the risk of frost injuries to seedlings, buds and shoots, and crown/leader dieback;
- There is evidence that, currently, there is a general increasing trend in net primary productivity developing for boreal temperate forests across North America, but the continuation of this trend in future years is unclear;
- Tree growth may benefit in some cases from higher CO_2 levels and its fertilization effects, and because of enhanced efficient water use and nitrogen availability (Johnston and Williamson 2005; Wang et al. 2006);
- Predicted changes in Alberta's climate suggest that growth and survival of white spruce will be seriously reduced in the central and northern parts of the province within the next 25 to 30 years (Rweyongeza et al. 2007b);
- Site index and productivity of lodgepole pine forests in the foothills of Alberta have been increasing, but it is unclear whether these factors are attributed to climate change influences, to improved management practices or to both;
- Provenance trials of lodgepole pine and jack pine in Alberta have demonstrated that increased productivity of these species is possible if they can be planted in areas identified as more optimal climatic environments where they could realize more of their genetic growth potential;
- The long-term effects of climate change on site index of species is largely unknown;
- Drought frequency, duration and extent are likely to increase in future decades in Alberta, and these events along with insect defoliation episodes and other forest disturbances could severely impact the growth, productivity and health of trembling aspen stands (Hogg et al. 2005; Hogg and Bernier 2005; Sauchyn and Kulshreshtha 2008; Sauchyn et al. 2008);
- Drought effects will be the single most important climatic factor in the Prairie Provinces causing reduced stem growth, top dieback and mortality of aspen and other tree species of the Boreal and Parkland zones;

- Future planting stock of hybrid poplars in the province will likely require increased genetic selection for drought tolerance, insect and disease resistance and for growth and productivity.

10.0 EFFECTS OF GHGS ON TREE GROWTH, SURVIVAL AND PHYSIOLOGY

Global atmospheric concentrations of GHGs, including CO_2, methane (CH_4), and nitrous oxide (N_2O), have increased substantially as a result of human activities since 1750. Most of the observed increase in globally-averaged temperature since about 1850 is believed to be due to the observed increase in anthropogenic GHG concentrations, which are expected to continue to rise over the next few decades (IPCC 2007b). Significant anthropogenic contributions to global warming potential also comes from tropospheric (near ground level) ozone (O_3) concentrations (IPCC 2007a), which are also increasing as a result of increasing industrial activity (Awmack et al. 2006). The changing concentrations of these GHGs, especially CO_2 and O_3, directly or indirectly influence forest health and tree condition (Percy and Ferretti 2003; Paoletti et al. 2007; Ainsworth and Long 2005).

Considerable research efforts have been undertaken to understand how trees and ecosystems will respond to the changing concentrations of GHGs. This section reviews the tree and plant physiological responses to increasing concentrations of GHGs and rising temperatures. These responses have been investigated by several experimental approaches, including greenhouses, climate chambers, open-top chambers, branch and single tree chambers, and recently various free-air release fumigation systems in tree plantations or forest canopies (Paoletti et al. 2004). However, it was recognized that enclosure systems have potential limitations when studying the effects of elevated CO_2 and O_3 on plants (Ainsworth and Long 2005). To overcome these limitations, large-scale free-air CO_2 enrichment (referred to as FACE experiments) procedures have been developed that allow for exposure of plants to elevated GHGs under natural and fully open-air conditions. FACE relies on natural wind and diffusion to disperse CO_2 or O_3 across the experimental area through an array of vertical and horizontal vent pipes that release jets of GHG-enriched air or pure GHG. The FACE experiments have been established on forest lands with exposed elevated levels of CO_2 of 475-600 ppm (i.e., CO_2 levels projected to 2050 or 2100) to encompass single or multiple tree species, groups of trees; to study soil fertilization and stress treatments; and to evaluate the effects of some insect and disease occurrences. An important aspect of FACE experiments is that they may explore both short and long-term (i.e., several years) effects of elevated levels of CO_2 (Ainsworth and Long 2005; Nowak et al. 2004). In addition, forest FACE studies, coupled with process-based models, are stated to be the best approach to gaining insights of the long-term effects of elevated CO_2 and O_3 on forest ecosystem processes and properties, and can examine feedbacks that affect soil nutrient and water availability and plant competition. FACE may also be used to explore interactions between climate variability, elevated CO_2 and stand functioning (Raison et al. 2007).

Effects of Increasing CO_2 and Temperature

Carbon dioxide is the main atmospheric component absorbed by trees and other plants as part of the photosynthetic process, and forms the basic building block for the primary production of carbohydrates in plants. Elevated atmospheric concentrations of CO_2 have potential to increase the photosynthetic uptake of CO_2 by as much as 33%, and thus provides a fertilizer effect for increased plant growth (Bhatti et al. 2006b; Holmes et al. 2006). This effect is expected to enhance the growth of some tree species and forest ecosystems, thereby allowing them to absorb more carbon (C) or C sequestration from the atmosphere. There is currently considerable debate, however, whether the enhancement of elevated CO_2 levels will actually result in net removal of CO_2 from the atmosphere at the ecosystem level (Bhatti et al. 2006b).

In general, elevated CO_2 levels, while enhancing photosynthesis, results in the decreased need for plants to open their stomates as widely as at lower CO_2 concentrations. This in turn allows plants to conserve water and to potentially use water more efficiently during plant growth. The fertilization effect, however, is highly variable among and between tree species and appears to be largely dependent upon environmental factors such as the availability of nutrients (especially nitrogen), water and temperatures (Beedlow et al. 2004; Holmes et al. 2006).

Numerous studies have examined the effects of elevated CO_2 concentrations and increased temperatures on the physiology and growth of tree species. The following is a summary of much of the research findings.

- There is now considerable evidence that the fertilizing effect of elevated CO_2 concentration is limited by environmental factors. In most experiments, elevated CO_2 increases photosynthesis, at least initially, but the long-term effect on ecosystem productivity is unclear. Elevated CO_2 may increase the carbon assimilation rate of CO_2, but it may not necessarily mean that growth will always increase because of limiting factors such as increasing temperatures, drought, changing climatic pattern, low N availability, effects of N deposition, tropospheric O_3, and the reallocation of carbon as a result of rising atmospheric CO_2 with potential effects on carbon sequestration (Beedlow et al. 2004).
- Seedling and young conifer and deciduous trees exposed to elevated CO_2 concentrations showed increased photosynthesis. For example, net photosynthesis of 40 year old Norway Spruce (*Picea abies*), Scots Pine (*Pinus sylvestris*), European beech (*Fagus sylvatica*), and black poplar (*Populus trichocarpa*) was increased 49 to 114% (Sigurdssen et al. 2002). In a study of trembling aspen seedlings of five different clones, elevated CO_2 exposure resulted in increases in height, diameter, volume and basal area. There were significant clonal differences in these responses (Dickson et al. 1998; Isebrands et al. 2001; Karnosky et al. 2005).
- Net primary production (NPP) is considered a convenient basis for comparing growth response due to elevated CO_2 concentration since it allows for fine root and leaf turnover (Raison et al. 2007). Based on four different forest plantation-FACE experiments that included loblolly pine (*Pinus taeda*), trembling aspen (*P. tremuloides)*, American sweetgum (*Liquidambar styraciflua)* and *Populus* spp., Norby et al. (2005) compared the response of ecosystem NPP over several years and all four plantation systems yielded similar percentage increases in NPP of about 23%. Additional growth enhancements reported for other FACE experiments have ranged between 25 and 43%, with similar increases in all plant parts including roots, wood and foliage (King et al. 2005). Aber et al. (2001) reported that shade-tolerant tree species tend to show greater growth response to elevated CO_2 concentrations than do shade-intolerant species because of more efficient use of light, water and nutrients.
- FACE studies to date of young plantation forests all show systematic increases in forest NPP and in net carbon accrual into the ecosystems over several years under elevated CO_2 concentrations (Raison et al. 2007). Less information is available on responses of mature trees to elevated CO_2 concentrations, and it is likely they may not show responses of the same magnitude as seedlings and saplings (Norby et al. 2005). Wang et al. (2006) reported evidence of an atmospheric CO_2 fertilization effect causing increased radial growth rates for open-grown white spruce in southeastern Manitoba.

- Elevated CO_2 concentrations caused a decline in N concentrations in trembling aspen and paper birch leaves and had no effect on the C:N ratio (Lindroth et al. 2001): a similar decline of N occurred in Douglas-fir foliage (Kilpelainen et al. 2005; Tingley et al. 2003). In studies of trembling aspen, paper birch and sugar maple, elevated CO_2 resulted in greater microbial soil N turnover (Holmes et al. 2003).
- Elevated CO_2 concentrations induced changes in anatomy and cell structures: e.g., earlywood and latewood widths were increased, wood density may be increased, cellulose concentration was decreased and tracheid lumen diameter was increased (Kilpelainen et al. 2005; Luomala 2005; Slaney 2006).
- Elevated CO_2 concentrations appear to alter the sensitivity of trees making them more prone to O_3 effects (Isebrands et al. 2004; King et al. 2005; Percy et al. 2002).
- Elevated CO_2 concentrations can have an effect on the reproductive fitness of species: for example, elevated CO_2 increased male and female flower production of paper birch, and had a positive effect on catkin size, weight and germination rate (Darbah et al. 2007).
- Increasing CO_2 concentration stimulates rapid stomatal closure and may cause a decrease in stomatal density (Keel et al. 2006; Paoletti and Grulke 2005).
- Elevated CO_2 concentrations can increase N concentrations in foliage and increase non-structural carbohydrates and secondary metabolites, all of which can alter tree resistance to insects and pathogens (Agrell et al.2005; Karnosky et al. 2002; Kopper and Lindroth 2003a, 2003b; Percy et al. 2002).
- Temperature increases may affect both photosynthesis and respiration rates in plants. Changes in air temperature in the spring or autumn can affect frost tolerance of tree needles/leaves and may also affect fruit and seed yields and quality. Air temperatures may also interact with soil and water content to affect growth responses of boreal tree species that increase with increasing temperatures. Increases in air temperature may also lengthen the growing season (Aber et al. 2001).

Effects of Increasing Ozone (O_3) Concentrations

Tropospheric O_3 is the third most important GHG contributing to global average radiative forcing. Current annual average background O_3 concentrations over mid-latitudes of the northern hemisphere range between 20 and 45 ppb with an annual cycle characterized by a spring maximum, peaking in May (Percy et al. 2007). A similar range in tropospheric levels of O_3 occur in Alberta, with peaks in spring and summer, and general trends have indicated increases of 1 to 25% at most Alberta monitoring stations since 1990 (Alberta Environment 2007). Historic increases in anthropogenic emissions of tropospheric O_3 precursor gases, nitrogen oxides, and volatile organic compounds have lead to a large increase in average surface level O_3 in the northern hemisphere over the past 100 years. Tropospheric O_3 is a growing air pollution problem and threatens forests in the northern hemisphere (Percy et al. 2007). Projected increased temperatures will likely contribute to higher rates of ozone formation (Beedlow et al. 2004; Fenn 2006).

Present lower tropospheric O_3 is formed from both stratospheric and photochemical tropospheric sources (Percy et al. 2007). Recently, the United States and Canada established the O_3 air quality standard metric as "the 3-year average of the annual 4th-highest daily maximum 8-hr average O_3 concentration". In Canada, the Canada-wide Standard for O_3 established a human health-based target level of 65 ppb O_3 (Percy et al. 2007). This standard is being adopted by Alberta Environment for monitoring O_3 levels (Alberta Environment 2005b). Percy et al. (2007) examined air quality standards in FACE experiments with five trembling aspen clones to help define O_3 exposure-response levels detrimental to tree growth. Using surface-level O_3 concentrations that ranged across North America from the standard metric form, they developed a spatial distribution map based on average O_3 concentrations that ranged from 55 ppb to 95 ppb. Much of Alberta is depicted within the lower range of 55 to 70 ppb. Their analysis from the FACE experiments indicated that for trembling aspen, O_3 levels above 70 ppb appeared to be clearly detrimental in causing growth reductions, although damaging levels of >60 ppb have been cited as detrimental to temperate and sub-polar forests (Fenn 2006). Based on their analysis, they estimated trembling aspen growth across North America due to 3-year average O_3 concentration and showed estimates ranging from 0 to 31%. Growth loss for much of Alberta's aspen forest predicted during 2001-2003 is in the range of about 3%.

Other effects of tropospheric O_3 pollution have been investigated by similar procedures as for CO_2. The following is a summary of some of the effects that are detrimental to tree health.

- Ozone has been shown to be a significant predictor of crown defoliation in forests in southwestern Europe, and there is a need for better indices explaining O_3 phytotoxic effects in the field. Young trees and seedlings appear to be more sensitive than mature trees (Paoletti et al. 2004).
- Short-term O_3 exposure stimulates stomatal closure as a reaction to increased internal CO_2 concentrations. Prompt closure of stomata accounts for plant resistance to O_3, and long-term exposure causes stomata to become sluggish in response to changes in environmental conditions (Paoletti and Grulke 2005).
- Elevated O_3 levels significantly increased epicuticular waxes on leaf surfaces of trembling aspen, paper birch and sugar maple as well as changes in wax chemistry (Karnosky 2005).
- On young trembling aspen, paper birch and sugar maple trees, exposure to elevated O_3 concentrations generally offset the growth and productivity enhancement due to elevated CO_2 concentrations. Of the three tree species, aspen showed the greatest sensitivity to elevated O_3, and birch and sugar maple were more tolerant (Karnosky 2005).
- Elevated O_3 concentration was associated with increased *Melampsora* leaf rust infection on trembling aspen, and caused an increase in abundance of aphids and a decrease in their natural enemies. Forest tent caterpillar pupal masses were decreased under elevated O_3 (Karnosky et al. 2002; Percy et al. 2002). The interactions of elevated CO_2 and O_3 levels can alter the susceptibility of trees to insect and disease species (Beedlow et al. 2004).
- In trees, elevated O_3 reduces CO_2 assimilation and alters C allocation. Ozone reduces C sequestration in trees and inhibits sequestration in soils (Beedlow et al. 2004).
- Fenn (2006) discussed the known and likely effects of N and O_3 interactions on forests in western U.S., noting that the physiological functioning of ponderosa pine trees has been dramatically altered, making them more prone to stress factors such as drought and bark beetle outbreaks (Jones et al. 2004). The long-term effects of the pollutants has drastically reduced fine root production, reduced the number of annual foliage whorls that are retained, increased the shoot:root ratio, resulting in greater C storage in the bole and branches, enhancing fuel accumulation as litter on the ground, and increasing the already high fire risk.
- A FACE study of five young hybrid poplar (*Populus* spp.) genotypes exposed to elevated O_3 levels resulted in decreases in height, total dry mass and basal area as well as in decreased leaf,

stem and root growth. In this study, the most rapidly growing hybrids had the largest decrease response to elevated O_3 exposure (Dickson et al. 1998). Elevated O_3 exposure can negate the positive growth effects of elevated CO_2 (Isebrands et al. 2001).

- FACE studies of young planted trembling aspen, paper birch and sugar maple trees exposed to elevated O_3 levels decreased gross N mineralization by 16%, and this effect was likely driven by decreased organic substrate input into the soil. Root biomass was reduced 18% (Holmes et al. 2006). These authors suggested there were likely changes in soil microbial metabolism since leaf litter concentration of soluble sugars, tannins, lignin and hemicelluloses were altered.

Effects of Nitrous Oxide (N_2O) Concentrations

Nitrous oxide is produced by both natural and anthropogenic sources. Primary human-related sources are from agricultural soil management, animal manure management, sewage treatment, mobile and stationary combustion of fuel, adipic acid production and nitric acid production. Nitrous oxide is also produced naturally from a wide variety of biogenic sources in soil and water, particularly from microbial action. These natural sources primarily result from bacterial breakdown of N in soils and in the oceans. Forests are important sources of emissions of N_2O into the atmosphere. In the soil, it is produced as an intermediate or end product from biological nitrification and denitrification. The strength of each process for producing N_2O is strongly influenced by environmental factors such as chemical and physical properties, climate and vegetation (Ambus and Zechmeister-Boltenstein 2005). These authors noted that the highest emissions (about 4 times greater) were in sites dominated by deciduous trees, and several of their coniferous sites showed little or no emissions. The studies suggested that the greatest proportion of the N_2O was produced by the denitrification process and a lesser proportion by nitrification. They concluded that changes in forest composition may have implications for regional budgets of GHGs (Ambus et al. 2006).

Effects of Methane (CH_4) Concentrations

Methane is a key component, along with CO_2 and O_3, driving climate change and atmospheric chemistry, and is the third most important GHG in the atmosphere after CO_2 and water vapor (Walter et al. 2007). Continued increases of global anthropogenic CH_4 emissions are predicted to be 35% higher in 2030 than in 2000 (Dentener et al. 2004). Methane has increased by approximately 250% since the pre-industrial era, exceeding the rate of CO_2 increase (IPCC 2001). Anthropogenic sources of CH_4 include rice agriculture, waste treatment, animal husbandry and biomass burning. Natural sources include wetlands, oceans, termites and hydrates (Walter et al. 2007). Recent studies suggest that significant new sources of atmospheric CH_4 are still being identified, such as production of CH_4 emitted from terrestrial plants under aerobic conditions but through an as yet unknown mechanism (Keppler et al. 2006). Enhanced CH_4 emissions are also proposed in association with permafrost degredation and the arctic thermokarst (thaw)-lake expansion as a positive feedback to climate warming (Walter et al. 2007). Some uncertainties therefore remain regarding total CH_4 emission estimates and in ascertaining the impact of these new sources on the global budget, and in examining net ecosystem fluxes (Ferretti et al. 2007; Sinha et al. 2007).

Methane is the most abundant hydrocarbon in the atmosphere and plays a key role in regulating stratospheric water vapor and tropospheric hydroxyl radicals (Sinha et al. 2007). The atmospheric lifetime of CH_4 is about 8.9 years and the soil is known to uptake methane (Sinha et al. 2007). The boreal forest ecosystem has been reported as both a sink and a net source for CH_4. However,

CH_4 emissions can vary seasonally, due to land use, soil temperatures and water table levels. It has been estimated that the boreal ecosystem as a whole contributes only about 7.5% of the total CH_4 emissions (Sinha et al. 2007).

In large parts of the Northern Hemisphere, photo-oxidation of CH_4 and carbon monoxide lead to net photochemical production of O_3, and this has resulted in elevated tropospheric levels of O_3 (Dentener et al. 2004). Once emitted, CH_4 is removed from the atmosphere by a variety of processes referred to as sinks. The dominant sink is oxidation by chemical reaction with hydroxyl radicals (OH). Methane consumption by temperate forest soils is a major sink but little is known about how tree species influence CH_4 uptake by soils. Overall, soils under hardwood species (e.g., aspen and birch) consumed CH_4 at higher rates than soils under conifer species, and an increase in soil moisture enhanced CH_4 consumption in soils under spruce, but had the opposite effect under Scots pine, and had no effect for other tree species (Menyailo and Hungate 2003). The specific response of soil uptake of CH_4 under elevated moisture was accounted for by the presence of different groups of CH_4-oxidizing bacteria.

In studies of soil-contaminated with natural gas (i.e., 80% methane), the oxidation of CH_4 was brought about by CH_4-consuming bacteria which multiply rapidly and, in the process, they consume much of the natural oxygen in the soil, thus leading to O_2-starvation while releasing CO_2. It has been stated that the effect of the consequent depleted low concentration of O_2 in the soil was the actual cause of tree mortality, rather than from any toxic effects attributed to the natural gas containing CH_4 (Davis 1977).

11.0 CLIMATE CHANGE IMPACTS ON FOREST DISTURBANCES

Over geologic time, changes in forest disturbance regimes are a natural part of all ecosystems. As a consequence of climate change, forests potentially face rapid alterations in the timing, frequency, intensity and extent of disturbances that are contributed by a number and complexities of climate variables. Disturbances can be both human-induced (e.g., harvesting) and natural, and can shape forest ecosystems by influencing their compositional, structural and functional processes (Dale et al. 2001). Burton and Roberts (2007) developed a classification system for describing the rationale and criteria of natural- and human-caused disturbances of forest ecosystems and proposed the following five attributes: a) the proportion of forest overstory remaining after disturbance; b) whether the surviving understory consists mostly of suppressed trees, dense shrubs or ferns, or a sparse herb or cryptogram-dominated ground layer; c) the extent of potential seed beds and elevated microsites; d) the strength of edge effects; and e) the spatial distribution (uniform, random, or clustered) of elements on each of these axes influences whether gap-level or stand-level dynamics will prevail. Collectively, these attributes determine habitat value and structural compositional development in disturbed forest stands. Each disturbance affects forests differently; most cause varying degrees of tree mortality, while others may contribute top dieback, growth reductions and severely impact community structure and biodiversity (Dale et al. 2001). Other concerns are the disruption of carbon balances, carbon sequestration, reductions in forest productivity and releases of GHGs (Kurz et al. 2008).

Natural disturbances that affect forests include fire, drought, windthrow (wind storms), ice storms, insect and disease outbreaks, landslides and floods. Each disturbance affects forests differently. The effects of each disturbance are partly tempered by prior adaptations since tree species present in a forest are a reflection of past disturbances (Dale et al. 2001). For example, natural stands dominated by lodgepole pine are a reflection of their fire origin and serotinous cone character.

Fire

Forest fires create new patches and fragmentation on landscapes and interrupt the normal processes of forest biomass accumulation. Fires are by far the most ubiquitous of disturbances as a spatiotemporal agent (Weber and Flannigan 1997). Fire effects on forests include mortality of trees, an acceleration of nutrient cycling, shifts in forest successional direction, loss of soil seed bank, induced seed germination, increased heterogeneity of the landscape, changes in surface-soil organic layers, and immediate release of GHGs to the atmosphere. Other subsequent effects include changes in habitat use for wildlife, recreation, changes in stand age-class structure, and decreased available fiber supply (Dale et al. 2001; Li et al. 2000; Volney and Hirsch 2005).

Fire regimes are characterized by their frequency, size, intensity, seasonality, type and severity, all of which are largely determined by weather conditions and forest composition and structure (Dale et al. 2001; Li et al. 2000; Volney and Hirsch 2005; Weber and Flannigan 1997). The climate elements that affect fire include temperature, precipitation, humidity, and wind speed and direction (Wheaton 2001).

Fire serves several functions in forest ecosystems such as influencing plant species composition, age class structure, regulating forest insects and pathogens, and maintaining productivity, diversity of species, and stability of different habitats. Forest fires can occur in all forest ecosystems but tend to be most intense in mature stands, and are generally more severe in coniferous stands compared to deciduous stands (Weber and Flannigan 1997; Johnston et al. 2006). Forest fires also affect tree and other plant distributions and may create opportunities for invasion and spread of invasive plant species (Oregon Wild 2007).

A forested area dominated by lodgepole pine in west-central Alberta was examined to determine how this forest landscape would be altered by potential climate change scenarios such as a doubling of CO_2 concentration and temperature increase in relation to forest biomass and forest fires. The simulation results projected increases in frequency of fire disturbance events and decreases in forest volume (Li et al. 2000).

Tree species that are adapted to regenerate following fire such as black spruce, lodgepole pine and jack pine, or favouring trembling aspen regeneration, may be favoured in the event of long-term increase in forest fire frequency. This could lead to increases in these spruce and pine species and trembling aspen at the expense of white spruce and other species less resistant to fires (Hogg and Bernier 2005; Hogg and Wein 2005; Johnston et al. 2006).

Future forest fire disturbances are expected to be more frequent, burn over larger areas, and fire severity could increase by 40-50%, although the magnitude and timing of these changes cannot be predicted (Johnston et al. 2006; Weber and Flannigan 1997). Increased fire frequency and area burned will have the effect of skewing stand age class distributions towards a younger age class structure. Another effect is the shifting of carbon fluxes from one of carbon sink to one of carbon source (Weber and Flannigan 1997). The GHG balance of Alberta's managed forests will be strongly affected by naturally occurring fire with high interannual variability in the area burned and by cyclical insect outbreaks such as by mountain pine beetle, spruce budworm and aspen defoliators. When combined, these disturbance events create uncertainties in whether the managed forests will become sources or sinks. These disturbance events are projected to be the driving force for the future carbon budget in the coming decades (Kurz et al. 2008).

Increased temperatures due to climate warming will affect soil moisture and increase risk of drought stress on trees; which in turn will create conditions more favorable to insect and disease attack, and result in tree dieback, growth reductions and mortality, and subsequent increased fuel for forest fires. Higher temperatures are expected to lengthen the growing season as well as extend the fire season, and thus increase the risk of more forest fire activity. Therefore it is important to recognize that all of these effects will interact with one another (Johnston et al. 2006; Volney and Hirsch 2005; Weber and Flannigan 1997).

Drought

Droughts can occur in most forest ecosystems. Drought conditions have a strong link with fire since the risk of fire increases with increasing drought duration and intensities, and depend upon annual and seasonal moisture and temperature changes. This results in moisture deficiencies and stress. Periods of drought occur at irregular intervals and may develop during spring to fall seasons and persist for several years (Dale et al. 2001). Drought stressed trees present conditions conducive for insect and disease attack (Beukema et al. 2007).

Climate change impacts in the boreal forest and parkland areas of the three prairie provinces have been intensively studied in relation to drought conditions occurring, especially during the period from 1950 to 2005. Effects of combined drought and insect infestations were shown to operate across a large spatial scale and to result in aspen dieback and in averaged growth reductions of up to 50% across a large portion of aspen forests. Moisture deficiency was the dominant factor limiting the growth and accumulation of above ground aspen biomass (Hogg et al. 2005; Hogg and Bernier 2005).

With the onset of dieback and mortality, aspen stands often deteriorate rapidly leading to stand breakup. However, because of stand breakup, canopy openings are created which allow for other species to invade as well as for root sucker regeneration by the clonal behavior of aspen (Frey et al. 2004). Although there are many uncertainties in predictions of future changes in moisture regimes in the southern boreal portion of the prairie provinces, projected climate to 2041-2070 indicates that moisture will become limiting in the southern most portions of the western boreal forest. This will allow a shifting northward of the southern boreal forest boundary and increase the area of drought-stressed forests in east-central and northwestern portions of Alberta (Hogg and Bernier 2005). In these drought-stressed areas, it is predicted that all ecosystem functioning would be impacted such as reduced forest productivity, drying of lakes, wetlands and peatlands, failure of conifer regeneration after fire disturbances and increased susceptibility to damage by insects and pathogens (Hogg and Bernier 2005; Volney and Hirsch 2005). A future increase in fire frequency suggests that there will be an increase in the area over which the fire return interval becomes less, thereby leading to an increase in the dominance of trembling aspen in the most fire-prone regions (Hogg and Bernier 2005).

Insects and Pathogens

Local, regional, and global changes in temperature and precipitation can influence the occurrence, timing, frequency, duration, extent, and intensity of insect and pathogen disturbances (Ayres and

Lombardero 2000; Dale et al. 2001). Climate influences the spread of insects and pathogens directly as well as the susceptibility of their forest ecosystems. Changes in temperature and precipitation can affect insect herbivore and pathogen survival, reproduction, dispersal and distribution. Indirect effects can include the impacts of climate on competitors and natural enemies that regulate the abundance of potential insect pests and pathogens. Changes in the intensity and frequency of insect herbivore and pathogen damage to trees can have a range of effects including a change in the degradation of forest resources, reduced biodiversity, and reduced overstory that influences changes in the understory diversity of flora and fauna. Changes in forest disturbance may also alter the physiological tree defenses and can produce feedbacks to climate through affects on water and carbon sequestration, and nutrient cycling of forest ecosystems (Ayres and Lombardero 2000; Logan et al. 2003; Volney and Fleming 2000).

Temperature is identified as the dominant abiotic factor directly affecting development, survival, range and abundance of insect species (Bale et al. 2002). In their assessment of the impacts of global warming on forest insects and pathogens, Logan et al. (2003) stated that global warming in particular will have a dramatic influence on pest insect species. They note that all aspects of insect outbreak behavior will intensify as the climate warms, and concluded that their assessment of outbreak behavior was applicable to such major pests as the mountain pine beetle, spruce budworm, gypsy moth and spruce beetle. Volney and Fleming (2000) reviewed the processes that lead to stand-replacing outbreaks of three major defoliator species (spruce budworm, jack pine budworm and forest tent caterpillar) of the boreal forest. They noted that many of these processes depend upon climate, either directly, such as extreme weather events (e.g., late spring frosts) that reduce larval survival and may terminate outbreaks, or indirect effects that operate mainly through influences of temperature and precipitation on host trees. Because of their major impact on forest ecosystems during outbreak periods, the damage effects caused by these defoliator species need to be included in any models that seek to describe the spatial and temporal distribution of carbon in the boreal forest. Additionally, the interaction of insects with fire needs to be accounted for in carbon sequestration forecasts (Volney and Fleming 2000). Natural insect enemies of these defoliators are also dependent upon climatic factors to maintain life processes and synchronicity with their insect hosts and the forest habitat in which they live. Key parasitoid and predatory species are associated with high mortality of late larval stages of the defoliator species and are likely a prime driver in causing the collapse of outbreaks (Volney and Fleming 2000). In other studies, Reynolds et al. (2007) reported that long warm summers were associated with abundance of caterpillar population fluctuations in northern hardwoods in northeastern United States.

An overview of potential climate change effects on forest diseases was presented by Beukema et al. 2007; Kliejunas et al. (2008) and Sturrock (2007). Some general conclusions are that, since tree species are projected to shift in distribution, their associated pathogen species will likely shift in concert; climate change effects such as drought, longer growing season, soil moisture, CO_2 fertilization, or increased/decreased precipitation periods will have an impact on host tree-pathogen interactions and pathogenicity. Host-pathogen interactions involving non-native tree hosts and introduced and invasive pathogens are likely at a higher risk to climate change (Ayres and Lombardero 2000). Plant defenses against pathogens involve the synthesis of biologically active secondary metabolites. Host-pathogen interactions tend to be regulated more by tree genetics rather than by environmental effects such as the case for Dutch elm disease. For such pathogens as *Annosus* root rot, *Armillaria* root rot, and black stain root diseases, tree physiological condition may be quite important while climate change may affect their epidemiology. It is therefore difficult to predict how specific climate scenarios will influence tree resistance to pathogens (Ayres and Lombardero 2000). Some indirect effects of climate also affect pathogens. For example, the distribution of Dutch elm disease could be influenced by climatic effects on the beetle species that vector the fungal spores. Similarly, the spread of pitch canker of pine will depend in part upon the ecology of its insect vectors (Ayres and Lombardero 2000).

Harvell et al. (2002) reviewed the potential consequences of temperature changes on infectious diseases and considered the hypothesis that climate warming could affect plant host-pathogen interactions by (a) increasing pathogen development rates, transmission, and number of generations per year; (b) by relaxing overwintering restrictions on pathogen life cycles; and (c) by modifying host susceptibility to infection. They suggested that greater overwintering success of pathogens will likely increase disease severity, and that, shorter, milder winters are expected to increase disease spread in the temperate zone.

Elevated CO_2 and tropospheric O_3 concentrations singularly or in combination have been shown experimentally to affect the productivity, physical and chemical leaf defenses of trembling aspen, and thereby effect changes in plant performance and increased insect and pathogen activity. For example, elevated O_3 and $CO_2 + O_3$ affected changes in leaf wax appearance, amount of wax, wax chemical composition, leaf surface, and wet ability. These changes resulted in 3- to 5-fold increases in levels of rust infection caused by aspen leaf rust (*Melampsora medusae* Thuem. f. sp. *tremuloidae*) (Karnosky et al. 2002; Percy et al. 2002). Elevated CO_2 and O_3 also influenced foliar quality of trembling aspen leaves by effecting changes in foliar nitrogen and tremulacin levels, but GHG had little or any affect on the feeding performance of forest tent caterpillar larvae (Kopper and Lindroth 2003a). In a similar choice experiment, increased CO_2 and O_3 levels altered the host-plant feeding preference, both between and within tree species preference of forest tent caterpillar larvae. The results showed that elevated O_3 levels increased forest tent caterpillar larval preference for paper birch leaves, compared with trembling aspen leaves, whereas elevated CO_2 levels had the opposite effect (Agrell et al. 2005). Kopper and Lindroth (2003b) also showed that elevated levels of CO_2 and O_3 both reduced oviposition of aspen blotch leafminer (*Phyllonorycter tremuloidiella* Braun) on trembling aspen leaves and reduced colonization of this insect by 42 and 49%, respectively. In another study in ponderosa and Jeffrey pine, O_3 exposure and atmospheric nitrogen deposition increased the susceptibility of these pine species to bark beetle attack (Jones et al. 2004).

The following is a brief survey of important insect and pathogen species likely to be problematic in future decades in Alberta's forests that can be linked to climate changes, either directly or indirectly.

Mountain pine beetle (MPB) (*Dendroctonus ponderosae*): Climate conditions have restricted the northward and eastward expansion of MPB in its previous outbreak history in British Columbia, but there is now strong evidence that climate change is influencing its survival and spread into the boreal forest region and threatening northern lodgepole pine and jack pine forests. Warmer winter and summer temperatures enhance overwinter survival, summer dispersal and tree attack success, while dry summer conditions induce drought stress on trees, enhancing susceptibility to attack (Carroll et al. 2004; Logan et al. 2003; Taylor et al. 2006). In southern Alberta, climate warming has allowed MPB to overwinter successfully at expanding population levels. This raises the risk level for its movement and spread from south to north along the Alberta foothills. This risk will likely increase in the coming years as predicted temperatures continue to rise. Lodgepole, limber and whitebark pines will be favored as hosts in its dispersal path.

Spruce budworm (SBW) (*Choristoneura fumiferana*): Damaging infestations of the spruce budworm in Alberta have occurred in practically all mature white spruce forests in the past, except for the foothills region. Most severe damages have occurred in the northern half of the province, coinciding with extensive stands along major river channels. Outbreaks have persisted over several years, appear not to be cyclic in nature, and have contributed to significant growth losses, tree mortality and changes in stand structure (Volney and Fleming 2000). In the coming decades, outbreaks are likely to continue as in the past, but may become less extensive over time as predicted changes occur in the distributional shift of boreal spruce forests.

Aspen Defoliators: Outbreak patterns of aspen defoliators, contributed by three dominant species, forest tent caterpillar (*Malacosoma disstria*), large aspen tortrix (*Choristoneura conflictana*), and Bruce spanworm (*Operophtera bruceata*) are likely to continue in similar frequency and extent as in past years. Since the life cycles of all three species require close synchrony with their host (trembling aspen) bud and leaf spring flush, life cycle development will likely progress more quickly as temperatures increase (Ives and Wong 1988). A large number of other less common defoliator species feed on aspen, many of which could potentially become significant pests under changing climate conditions. Overall impacts of aspen defoliators, combined with more frequent droughts will likely be more severe in the coming years, compared to that reported by Hogg et al. 2002, 2005).

Spruce Beetle (*Dendroctonus rufipennis*) and Wood Borer Species: High winds will continue to cause areas of windthrow periodically, and these disturbances may occur at increasing frequency. Windthrow in mature white spruce stands creates single large breeding materials attractive to the spruce beetle which can build up rapidly and expand to kill adjacent live-standing trees (Beukema et al. 2007). Such downed material, along with fire-killed trees, provide prime breeding habitat for conifer wood boring species such as sawyer beetles (*Monochamus* spp.) and northern spruce borer (*Tetropium* spp.). Future population levels and damages caused by these species are likely to increase in the coming decades due to a combination of increasing drought, forest fire and storm events. Drought weakened aspen is prone to increased attack by the poplar borer (*Saperda calcarata*) (Brandt et al. 2003; Hogg et al. 2002). Similarly, decline of drought-stressed paper birch develops rapidly with increased susceptibility and attack by the bronze birch borer (*Agrilus anxius*) (Ives and Wong 1988).

Climate change could have positive, negative or no impact on individual tree pathogens. Drought effects and temperature and precipitation extremes are likely to have a significant impact on abiotic diseases, causing drought stress in trees, soil moisture deficiencies, frost injuries, dieback, and mortality of overstory trees, which can rapidly alter ecosystem properties. Drought stressed trees are likely to be more prone to canker-type diseases such as Hypoxylon canker (*Biscognauxia* sp.) of trembling aspen and to heart rots of tree stems (e.g., *Phellinus* spp. *Sterium* sp.) affecting aspen and conifers. Drought induced conditions will also be favorable for increased infections in root systems caused by Armillaria root rot (*Armillaria* spp.) and Tomentosus root rot (*Inonotus tomentosus*) (Beukema et al. 2007; Kliejunas et al. 2008).

Pine stem rust diseases, spruce cone rust, conifer needle cast diseases and leaf diseases of aspen all are favored by moisture conditions to enhance infection and spread (Allen et al. 1996). The implications of climate change on these diseases are difficult to predict. Each disease involves individual pathogen-host interactions and associations, and much of the information on their epidemiology is lacking (Kliejunas et al. 2008).

Native rust species of pine, such as comandra blister rust (*Cronartium comandrae*), stalactiform blister rust (*C. coleosporoides*), and western gall rust (*Endochronartium*), as well as the introduced and invasive white pine blister rust (*C. ribicola*) are all influenced by atmospheric conditions and host populations, each of which is affected by climate change. Information on the range of pine hosts and microclimates to which stem rusts have already adapted provide an indication of future infestations. The rust life cycle determines in part where infestations become established as well as their rate of increase and persistence. Spore development, dispersal and germination on host tissues are directly affected by weather factors such as temperature, humidity and air flow (Kliejunas et al. 2008).

Dwarf mistletoe (*Arceuthobium americanum*) infection on lodgepole and jack pine hosts is currently absent from more northerly and higher elevation ranges of these tree hosts. This may be partly because of colder temperatures which restrict reproductive development of the mistletoe plant (Brandt et al. 2004; Kliejunas et al. 2008). Future warming trends may favor increased expansion of spread and infection.

Wind Storms, Landslides, Floods and Frost

Global warming is forecast to result in a greater frequency of extreme weather events such as wind and ice storms, flooding, landslides and killing frosts. Increased wind storms can result in areas of extensive windthrow, especially in mature forests. Trees may be snapped off at various lengths along the stem, at tree base level, or uprooted during severe wind storms. Subsequently, affected trees are weakened or killed and become prime targets for invasion by insects such as a variety of bark beetle and wood borer species. In Alberta, all known outbreaks of the spruce beetle (*Dendroctonus rufipennis*) have been preceded by extensive windthrow of mature white or Engelmann spruce. This apparently was not the case in the recent spruce beetle outbreak in southern parts of the Yukon where it developed as a result of severe drought-stressed spruce (Garbutt et al. 2006). Wind storm disturbances can create large patches of tree damage which can result in canopy disruption, reduced tree density and size structure, and change local environmental conditions (Dale et al. 2001). The disturbances may trigger advance regeneration, seed germination, accelerated seedling growth, and alter the successional pattern (Dale et al. 2001). Shallow-rooted species such as white spruce, and trees along margins of openings, tend to be most vulnerable to windthrow. High winds accompanying hail storms may also cause extensive crown dieback, branch and stem bark wounds, and defoliated foliage and branch tips. A positive correlation between monthly tornado frequency and mean monthly temperature has been reported in western Canada (Dale et al. 2001). It can be inferred from this relationship that increased tornado activity will occur under a warmer climate scenario. Tree and forest damages by wind disturbances vary widely in space and time.

Other direct effects of wind during forest fires relate to the direction, rate of spread and fire intensity (Weber and Flannigan 1997). Winds may also assist in the spread and mass movement of adult insect species, thus aiding in their dispersal over short and long distances (Jackson 2006).

Increased general windiness is expected to occur in Scandinavian countries because of rising temperatures, and the frequency and magnitude of extreme winds will be important. There is concern that rising temperatures will affect soil freezing, thus making trees less wind-firm during the late fall and early spring periods, and thereby increasing the risk of windthrow. Increased incidence of windthrow may occur especially if there is a seasonal shift in wind frequency pattern coinciding with weaker tree anchorage during frost-free periods. Calculated amounts of tree-felling winds in Finland have been estimated to increase from 55 to 80% in the south and from 40 to 50% in the north in a climate scenario of a mean annual temperature increase of 4^{o}C (Bergh et al. 2004).

Ice storms, floodings and landslides historically have occurred in Alberta but forest and tree damages have been somewhat infrequent and relatively small in comparison to other major disturbances such as fire, drought and insects.

Frost injury to trees may occur because of thaw-freeze conditions during winter and spring (Hogg and Bernier 2005). Warming temperatures in the spring can result in early bud flush of tree species such as trembling aspen and white spruce with consequent bud kill from late-spring frosts (Cerezke and Volney 1995). Spring flushing dates may vary considerably for individual aspen clones, and late spring frosts have caused leaf kill over entire clones that have flushed prior to a killing frost.

Summary of the impacts of Climate Change on Forest Disturbances for Alberta

- Natural disturbances that will affect forests include fire, drought, insect and disease outbreaks, hail and wind storms, landslides and floods. Each disturbance will affect forests differently;
- Future forest fire disturbances are predicted to be more frequent, burn over larger areas and with increased severity;
- Major effects of fires will create new patches and fragmentation on landscapes, interrupt the process of forest biomass accumulation, cause tree mortality, accelerate nutrient cycling, shift the direction of forest succession, cause changes in surface soil organic layers, and cause an immediate release of GHGs to the atmosphere. Other changes are shifts to younger stand-age class structures, decreased fiber supply, shift in carbon fluxes from sinks to sources, and changes in hydrology, wildlife and recreational values;
- Tree species adapted to reproduce following fire (e.g., black spruce, lodgepole pine jack pine and trembling aspen) will likely be favored over other species not similarly adapted to fire;
- Fire disturbances will interact with drought stressed trees, tree mortality and dieback (increased fuels), decreased soil moisture, and increased insect/pathogen activity;
- Increased water scarcity leading to drought conditions is considered to be the most serious climate risk for the prairie provinces. Increased drought frequency, duration and extent are forecast for Alberta (Sauchyn and Kulshreshtha 2008; Sauchyn et al. 2008);
- All ecosystem functions will be impacted by drought effects;
- Changes in temperature and precipitation will affect the life histories, dispersion, reproduction and population dynamics of forest insect species, and the infection and epidemiology of tree pathogens. Some pest species especially affected by climate change include the mountain pine beetle, spruce beetle, spruce budworm, wood borers, root diseases and stem cankers. There will also likely be increased risks of new pests and invasive species;
- Increased variability in weather systems may result in more frequent and severe wind and hail storms that have potential to cause windthrow and other tree damages, which in turn will increase the fuel load for fires and provide habitat for bark beetle/woodborer infestations;
- Increased tree injury due to frost events is likely because of a predicted increase in freeze-thaw conditions during winter and spring.

12.0 CLIMATE CHANGE IMPACTS AND FOREST GENETICS

Forest tree species have experienced many environmental changes during their evolutionary and ecological histories. Environmental changes may have been gradual or abrupt, occurring over relatively few years. Both the degree and rate of change are of concern for the future of tree species and their responses to global climate change (Bergh et al. 2004; Colombo et al.1998; Hamrick 2004) as their options to responses to a changing environment are genetic adaptation, migration or extinction (Aitken et al. 2008). There are concerns that tree species may not have adequate genetic variation to adapt to climate modifications in the future, and that environmental changes may occur too quickly for tree species to adapt. Hamrick (2004) examined the criteria of how trees might respond to projected climate and environmental changes expected to occur over the next several decades. He concluded that tree species will respond in a variety of ways; some will be reduced in ranges, others may expand, while some may become extinct, especially if environmental changes persist over long periods. Tree species with limited ranges and/or reduced genetic variation may be more prone to extinction. Although much of the genetic variation of tree species resides within rather than among populations (Hamrick 2004), variation among populations indicates an adaptive response of the species to environmental selection pressures. Thus, loss of tree populations coupled with the fact that evolution by natural selection is much slower than the predicted rate of climate change would severely diminish the ability of the species to adapt to a changing climate. However, with knowledge of species population structure and its relationship with climate, assisted migration through choice of wild or genetically improved populations and planting in appropriate environments would reduce the loss of forest productivity due to climate change over the short term. Over the long term, evolution by natural selection would re-establish an equilibrium between the species and the changed climate.

With the projected shifting of tree distributions, there may be extensive habitat fragmentation, which could challenge the maintenance of genetic diversity. However, Hamrick (2004) maintains that the longevity of individual trees may retard population extinctions and allow individuals and populations to survive until habitat recovery occurs, and that the wind-pollinated characteristic of many species will serve to counteract the effects of genetic drift. The evolution based on natural selection in response to environmental changes in trees tends to be slow because of their long generation time. However, trees rely on their phenotypic plasticity (i.e., the ability to adapt in response to environmental cues or genetic-environmental interaction) to withstand the wide variations in weather that occur from year to year. A literature review by Rweyongeza and Yang (2005a) shows that species with wide natural ranges including white spruce (Rweyongeza and Yang 2005c), lodgepole and jack pines (Rweyongeza and Yang 2005d) and tamarack (Rweyongeza and Yang 2005e), have high genetic variation. Such species have a better chance of survival in a changing climate than species with endemic distribution and low genetic variation.

Migration rates following climate change will differ for each tree species, depending upon how efficiently they are able to disperse and whether migration corridors exist between favorable environments. Physical barriers such as lakes and mountain ranges will impede some migrations, and in many cases migration can be assisted by planting programs. Migration may also be affected by seed and pollen production, dispersal rates, and whether conditions are favorable for fertilization. Species such as white spruce and trembling aspen have good seed dispersal rates; for black spruce and balsam fir, seed dispersal rate is indicated as medium, and it is poor for jack pine (Colombo et al.1998).

Tree species most susceptible to changes in climate are those that are localized, highly specialized, poor dispersers (limber pine may fit this category), or genetically depauperate (red pine). In a changing environment, species can track their original environment through migration or genetically adapt to the new environment. Due to limited migration ability, genetic variation and thus ability to adapt are the major means of survival for forest tree species. Thus climate change poses the greatest risk to species with limited genetic variability and endemic distribution. Assisted migration to favorable climate may be necessary to save species with limited ability to adapt to new environments (D. Rweyongeza and L. Barnhardt, personal communication). Populations most at risk tend to be isolated and occur at the edge of a species range, and include those that occupy montane and alpine sites (e.g., whitebark pine, alpine larch and interior Douglas-fir in Alberta) (Colombo et al.1998).

Provenance trials in general have shown that climate determines survival and growth when trees are planted on a range of environmental sites. The knowledge of climate factors that affect the genetic differentiation of tree species is essential for matching populations to planting sites in the present and in future predicted scenarios (Rehfeldt et al. 1999; Rweyongeza et al. 2007b; Wang et al. 2006). The planting of provenance trials on a range of sites with different climates and ecology makes it possible to evaluate the effects of climate change on survival and growth of individual populations. In a study of planted white spruce provenances in Alberta, it was shown that the between-population genetic variance was 10.6% and 6.6% of the between-population phenotypic variance across sites. Three climatic regions were found to exist in Alberta in which variation in growth potential for white spruce is clinal. The annual moisture index (AMI) (i.e., ratio of degree days >5°C and mean annual precipitation) was a major determinant of survival and growth at test sites, and at the AMI level predicted for 2030-2039, survival and growth are likely to decline in central and northern Alberta but increase in the Foothills and Rocky Mountain regions (Rweyongeza et al. 2007b).

In Sweden, it is recommended that, since the first year during and immediately after planting conifer seedlings is the most critical for survival and growth, all genetic material requires careful selection for its adaptation to the climate it will experience during the first years (Bergh et al. 2004). These authors suggest that if seedlings are planted that are adapted to predicted warmer climates, they may experience a high rate of mortality. The Swedish tree breeding program focuses on Norway spruce, Scots pine, lodgepole pine and silver birch. However, should drastic climate changes occur in the future, Sweden may examine other adapted material for their main forestry species. They suggest that the use of a broader range of tree species could help spread the risks of an uncertain future, and that climate change may alter the relative competitiveness among species.

In British Columbia, Wang et al. (2006) have re-examined the use of response functions in selecting lodgepole pine populations for future climates. They predict that their new deployment strategies using the best seed sources for future reforestation programs may help to mitigate the negative impact of climate change and may increase productivity in some cases.

At a recent Symposium in British Columbia on Future Forest Ecosystems addressing tree species and genetics (BC Ministry of Forests and Range 2006), some specific suggestions emphasized the need to increase tree species and seed lot diversity on the landscape, that current policy needed to focus on “fringe species” (e.g., whitebark pine, alpine larch, limber pine, etc.) as well as the commercial preferred species; that greater acceptance be encouraged for broadleaf and fire-resistant species; and that forestry move toward more uneven-aged stand management.

A survey of tree species of concern in Canada was conducted to identify species that may be in need of genetic conservation (Beardmore et al. 2006). Results of this survey indicated a serious damage potential for whitebark pine and limber pine due to infections by white pine blister rust (*Cronartium ribicola*). They noted that the range or frequency of whitebark pine was decreasing and that there were uncertainties about viable seed sources.

Increases in atmospheric CO_2 and O_3 will result in increases and/or decreases in growth of some species. Under these conditions, certain genetic traits or genotypes may be selected over others (Colombo et al. 1998, Dickson et al. 1998, 2001; Gupta et al. 2005; Karnosky et al. 1997). Trees subjected to stress conditions are likely to be more susceptible to insects and pathogens.

Summary of Climate Change Impacts and Forest Genetics for Alberta

- Options for tree species in response to a changing climate and environment are genetic adaptation, migration or extirpation;
- Tree species are likely to respond in a variety of ways to climate change depending upon their inherent genetic variability. Tree species occupying limited ranges and/or reduced genetic variability may be more prone to extinction;
- The projected shifting of tree distributions may lead to extensive forest habitat fragmentation, and this could challenge the maintenance of genetic diversity;
- Canadian boreal conifers appear to have high genetic variation, which is the raw material for natural selection and adaptation in a changing climate.
- The potential for tree species to migrate following climate change will differ for each species, depending upon how efficiently they are able to disperse and whether migration corridors exist between favorable environments;
- Genetic variation and the ability to adapt are the most important means of survival for forest tree species;
- Populations of tree species most at risk of survival or extinction tend to be isolated, occur at the edge of a species range, and occupy montane and alpine sites;
- Increases in CO_2 and O_3 concentrations will likely have variable influences on the growth of tree species, favoring some genetic traits or genotypes over others;
- Survival and growth of several conifer species are likely to decline in central and northern Alberta, but increase in the Foothills and Rocky Mountain regions.

13.0 CLIMATE CHANGE AND RISKS OF INVASIVE SPECIES

An "invasive species" is defined as a species that is not native to an ecosystem and whose introduction does or is likely to cause economic or environmental harm, or harm to human health (Chornesky et al. 2005). In managed forests, invasive species can detrimentally affect all of the attributes of forest ecosystems that sustainable forestry seeks to retain such as biological diversity, tree health, productivity, water and soil quality, contribution to the carbon cycle, and socioeconomic values. For example, invasive pathogens or insect pests that kill or weaken trees can alter the ecology, function and value of diverse forest ecosystems. Invasive plants may also modify forest ecosystems by altering fire and hydrological regimes, food webs and the recruitment of tree species (Chornesky et al. 2005).

Invasive species may include insects, pathogens or plants. Once invaded into a new habitat, its presence and persistence is often long lasting and cumulative. Movement of an invasive species into Alberta, for example, may come from an adjacent province within Canada, the United States, or be of international origin. Global trade patterns and international travel frequency have increased the risk of new foreign pest species' introductions. Also, solid wood packaging materials have often provided the pathway of invasive species entry from a foreign country (Allen and Humble 2002). Continued increases in human access, forest fragmentation and disturbances all provide increasing opportunities for invaders to penetrate and become established in Alberta's forests. The ultimate ranges of introduced species are largely determined by climate and human activities. Climate change will likely amplify these processes by altering disturbance regimes and the geographic ranges of forest and pest species (Dale et al. 2001).

Dukes and Mooney (1999) identified several impacts of climate change that may potentially affect the prevalence of an invasive alien species: increased atmospheric CO_2 concentration; global warming and precipitation changes; increased nitrogen deposition; altered disturbance regime; and increased habitat fragmentation. Rising CO_2 concentrations may have positive or negative effects on native and non-native plant species, or affect species differentially in ways that favor the survival and spread of a non-native species over native species. Growth responses to increased CO_2 concentrations may vary in different plant communities, thus making predictions difficult. Stimulated plant growth may lead to more rapid fuel loading, which in turn may increase the frequency and severity of fires. There is also evidence that rising CO_2 levels might slow the process of succession in grasslands and thereby increase the potential of dominance of a non-native species (Dukes and Mooney 1999). Anthropogenic climate change may act as a major cause of plant and animal species extinctions (Thomas et al. 2004).

Changes in global temperatures will result in changes in precipitation regimes. Locally these changes will directly favor some species over others, resulting in range shifts. Under some circumstances, a short-term increase in water availability may facilitate the long-term establishment of an alien plant species. In some situations, invasion by certain grass or shrub species such as sagebrush (*Artemisia tridentata*) may be favored by warmer temperatures. Some plant species have a higher optimum temperature for photosynthesis (e.g., several weed species) and therefore they may be favored by climate change over other species that have a lower optimum temperature. Rapid dispersal is a characteristic of many biological invaders, and this function could be influenced by changed weather patterns such as higher temperatures or increased frequency of winds and floods (Dukes and Mooney 1999). In some grassland habitats, the invasion of alien species could reduce the nutritional quality of the native grass species (Stone et al. 2006). Impacts of increased nitrogen into habitats are likely to be highly variable by region. Increases in nitrogen deposition favor fast-growing plant species, and in North America, many of the plants most responsive to nitrogen tend to be alien grass species. The introduction of two invasive tree species (Norway maple, *Acer platanoides*, and tree of heaven, *Ailanthus altissima*) into temperate forests in northeastern United States altered the functioning of these ecosystems by increasing cycling rates of nitrogen mineralization, net nitrification, calcium mineralization and nutrient availability (Gomez-Aparici and Canham 2008).

Changes in land-use patterns that increase habitat fragmentation and alter disturbance regimes will increase the prevalence of non-native species. Also, the interactions among the elements of global climate change may affect the prevalence of biological invaders (Dukes and Mooney 1999). Alterations of forest nutrient cycles are contributing to escalating rates of species invasions and impacts. Both climate and land-use changes alter the physical environment and disturbance regimes in ways that can favor non-native species and alter forest ecosystem vulnerability to invasions (Chornesky et al. 2005). Stand disturbances that lead to tree mortality, stand openings and forest fragmentation can pave the way for increased invasion of noxious weed species.

Increasing connectivity between protected areas to facilitate migration of particular species populations is commonly proposed as one method of coping with climate change. However, Sauchyn and Kulshreshtha (2008) have suggested that increased connectivity may favor alien invasions or support the arrivals of new competitors such as tree pathogens that may have the potential to hasten the decline of some ecosystems.

Some examples of invasive alien insect and disease species that have arrived in Alberta and that have high tree destructive potential include the mountain pine beetle, Dutch elm disease and white pine blister rust. Other damaging insect species of European and Asian origin currently present in Canada but not as yet known in Alberta, include the Asian longhorned beetle (*Anoplophora glabripennis*), brown spruce longhorn beetle (*Tetropium fuscum*), emerald ash borer (*Agrilus planipennis*), and larch casebearer *(Coleophora laricella*).

An example of a recent invasive pest species arrival is Septoria canker (*Septoria musiva*) to the lower mainland of British Columbia. This fungal pathogen causes leaf spots and stem cankers on hybrid poplar stems and is one of the most important pathogens of hybrid poplars in eastern North America (Callan et al. 2007). This example of a fungal pathogen introduction points out some of the difficulties encountered for early detection, species identification, and in developing appropriate mitigation measures (Callan et al. 2007).

14.0 FOREST HEALTH AND CLIMATE CHANGE FORECASTS FOR ALBERTA

In the sustainable management of Alberta's forests under a changing climate, two over-riding goals are important as a guide for future forest management considerations. These are:

- To maintain Alberta's forests in a healthy condition; and
- To strive to maintain a carbon balance in Alberta's forests and a net carbon sink.

From a forest health perspective, there are a number of issues that should be considered:

- The present forest inventory in Alberta indicates that stands are mostly less than 140 years old. Age class distributions for pure coniferous, pure deciduous, mixed coniferous and mixed deciduous appear in all 20-year age classes with some distributional differences (Smith et al. 2003). For example, for pure coniferous and mixed coniferous, there is a skewing to older age classes, whereas in pure deciduous and mixed deciduous, the skewing is more toward younger age classes. Future disturbance events (fire, drought, insects, harvesting) will decrease older age classes over time and shift the skewing to younger age classes. This will have the general effect of decreasing the incidence of insect and pathogen species that are associated with mature trees and stands, while at the same time increasing opportunities for pests attractive to young stands. In addition, the Pine Strategy established by Alberta Sustainable Resource Development (ASRD) for mountain pine beetle management, where the goal is to reduce the area of susceptible mature lodgepole pine stands by 25% over the next 20 years, will contribute to further skewing toward younger age classes (Alberta Sustainable Resource Development 2006).

- The impact of climate change, in combination with predicted increases in forest disturbances, provides challenging questions concerning forest succession dynamics. In the case of lodgepole pine ecosystems in Alberta, as in British Columbia, there are concerns about dynamics of forest succession in the aftermath of mountain pine beetle (MPB) attack and in relation to fire risk dynamics (Dykstra and Braumandl 2006; Forest Practices Board 2007; Hawkins and Rakochy 2007; Hawkes et al. 2004, 2005; Page and Jenkins 2007b). Following epidemic population levels, MPB activity has been shown to alter stand composition, structure and succession pattern (Page and Jenkins 2007a). Lodgepole pine is a seral species in many ecosystems, but can be a self-perpetuating climax species where climate, disturbance and edaphic factors limit the regeneration of other species (Hawkes et al. 2005). Lodgepole pine is considered a fire-dependent species, which allows it to reproduce successfully because of its serotinous cones. It also produces non-serotinous cones, thus permitting it to regenerate successfully in the absence of fire. The disturbance history of lodgepole pine sites, however largely determines the age-class structure of subsequent stand development; i.e., at the landscape level, most stands are likely to be even-aged if of intense fire origin, but can be uneven-aged if disturbed by consecutive attacks of MPB for example, or by non-stand-replacement fires such as surface fires. Thus, lodgepole pine may form a mosaic of mostly even-aged stands interspersed with uneven-aged patches over the landscape, depending upon the disturbance history (Hawkes et al. 2005). An understanding of the impact of MPB outbreaks in unharvested pine stands, and of other pest species that kill trees, is important for the following reasons:

    1. It is advantageous to be able to predict the post-outbreak development of the stand age-class structure and species composition for long-term stand management and inventory prediction;

    2. The accumulation of dead woody fuel materials for fire behavior and risk planning;

    3. The fall-down rate of killed trees and snags for habitat changes;

    4. Regeneration and stand structure for growth and yield, and intermediate timber supply prediction;

    5. Deciding management options available such as salvage harvesting, site rehabilitation requirements, silvicultural treatments, etc.;

    6. Assessing functional aspects of the stand for protection of watersheds, wildlife habitat, and other values.

While there is considerable uncertainty concerning the future forest succession dynamics in lodgepole pine stands, recent surveys in post-MPB outbreak areas of central-interior British Columbia have indicated that 30 to 60% of the sites surveyed can be considered satisfactorily stocked. The MPB tree mortality, after several years, has resulted in a lodgepole pine multi-age and multi-size stand structure consisting of residual saplings, subcanopy and canopy level trees, some ingress of new lodgepole pine regeneration as well as a mix of other tree species.

The opening of the canopy has resulted in substantial growth release on residual tree stems as well as an increased lower canopy shrub layer (Forest Practices Board 2007; Hawkins and Rakochy 2007). However, 40% or more of the plots surveyed were most likely of pure pine character, and these stands tended to be void of any regeneration and may be considered understocked. These stands may require management intervention to bring them to a fully stocked condition.

- Mixedwood stands consisting primarily of trembling aspen and white spruce are a major component of the boreal forest, being especially abundant in the prairie provinces where the boundary between boreal forest and grassland is strongly influenced by moisture (Hogg and Wein 2005). This raises concerns about the future mixedwood boreal forest if drier conditions continue to develop over the next several decades. Potential impacts likely to develop include drought-induced regeneration failure of white spruce and black spruce following fire, drought stress of mature trees with gradual crown dieback, and large-scale dieback of aspen caused by drought and insect defoliation (Hogg et al. 2002, 2005; Frey et al. 2004). Climatically dry areas also occur in northern Alberta and adjacent areas of the Yukon and Northwest Territories. In a study of post-fire conditions in mixedwood forest sites in the southern Yukon, regeneration and regrowth were abnormally slow some 40 years after the burn. The growth of both aspen and white spruce were strongly moisture limited and the apparent lack of white spruce regeneration was attributed to poor seed dispersal, poor germination of seed and low survival of seedlings (Hogg and Wein 2005).

  The traditional view of boreal mixedwood succession is a progressive change from mainly hardwoods (e.g., aspen, poplar, birch) to mainly conifers (e.g., white spruce). Aspen is also a seral species and is characterized by high levels of stocking after a disturbance such as fire, but in mixedwood stand development, conifers increase, aspen mortality increases and aspen regeneration decreases (Peterson and Peterson 1992). On upland sites, succession from aspen to white spruce after fire disturbance may follow either of two separate patterns: in most cases there is rapid and dominant development of aspen (and likely birch) well before conspicuous development of white spruce. The second pattern, if a spruce seed source is available and site conditions are favorable, is for white spruce and aspen to invade concurrently and an even-aged white spruce stand develops. Both aspen and white spruce can develop at the same time after fire, but a light fire may allow immediate aspen development and delayed spruce regeneration developing over several subsequent years. The successional fate of mature white spruce forests in the absence of recurring fires is not well understood for the boreal and mixedwood regions (Peterson and Peterson 1992). The vegetative reproduction habit of aspen clonal root systems, when stimulated by fire, provides a strong survival and successional advantage for aspen over white spruce, which relies on seed germination. This advantage is likely to be exemplified as climate change intensifies, thus favoring more aspen stand development than white spruce.

- The current outbreak of the mountain pine beetle in Alberta will likely continue for several years and a high level of surveillance and mitigative measures will be necessary to execute annually. Post-outbreak conditions will require continued monitoring for endemic populations which are likely to persist in a number of areas from southwestern Alberta to the northwest and central regions.
- Infestations of the spruce budworm will remain chronic in mature and overmature spruce stands similarly as in past years, but the aerial extent of infestations is likely to decrease over time.

- Increased fire, drought and windthrow events will require increased surveillance of these disturbance areas to monitor for increases in bark beetle and wood borer populations.
- Increased areas of white spruce planted and natural regeneration will likely require increased surveillance for drought-caused mortality and possibly frost injuries occurring in late winter or spring. White pine weevil and yellow-headed spruce sawfly incidence in young stands will likely remain similarly as at present.
- Increased areas of young pine regeneration will be prone to infections by pine stem and needle rust diseases and a variety of needle cast diseases, but infection levels may not change from current levels. Similar incidences of attack are likely from terminal weevils as well as from Warren's root collar weevil. However, the incidence of Armillaria root rot in pine and other species is likely to increase with climate change because of projected increased drought stress.
- In most forested areas, risk of damages caused by extreme weather events (wind, hail, snow and ice storms, etc.) are predicted to increase.
- Because of the predicted impacts of climate change on forest ecosystems and changes in tree distributions, there is the likelihood of some insect and pathogen species that are not currently recognized as pests, becoming pests as new situations are created. There will also be increased risks of non-native or invasive species invading new ecosystem niches and becoming established. Two examples of species not previously reported as important pests in Alberta might include western spruce budworm (*Choristoneura occidentalis*) on Douglas-fir and linden looper (*Erranis tiliaria*) on trembling aspen.
- Drought condition has been identified as an event likely to be more frequent and widespread in future years, contributing to decline and dieback of all tree species growing in central to northern areas of the province. These declining conditions will create stand openings and successional changes in the understory, as well as interactions with fire activity because of increased dead fuel materials. Risks include a reduction of the productive forest land base and changes in land-use policy.
- The importance of maintaining a carbon balance in Alberta's forests will require incorporating carbon management into forest management objectives and protecting forest carbon sinks. Management of the carbon balance and sequestration will likely require the implementation of a monitoring and reporting system, perhaps in coordination with other provincial jurisdictions and national strategies such as the new National Forest Pest Strategy. The establishment of a monitoring system will require exploring and evaluating existing environmental and biological monitoring systems and procedures.

15.0 FOREST MANAGEMENT RESPONSES AND MEASURES TO HELP MITIGATE AND ADAPT TO CLIMATE CHANGE

A number of publications offer adaptation strategies (i.e., actions that help ecosystems accommodate changes adaptively) to assist in the management of forest ecosystems in the context of a changing climate. Information, suggestions and specific guidelines are offered in the following publications: Bauer et al. 2006; Hogg and Bernier 2005; Johnston et al. 2006; Millar et al. 2007; Mortsch 2006; Oregon Forest Resources Institute 2006; Sauchyn and Kulshreshtha 2008; Spittlehouse 2007.

Papadopal (2000, 2001) and Parker et al. (2000) suggested a number of climate change mitigation measures which were stated to be compatible with present day forest management practices. Although there is large uncertainty in predictions of future forest distribution, composition and productivity, future forests are gaining in importance as a vehicle for carbon sequestration, and future forest management will likely be evaluated on their effectiveness in fulfilling this function. The practices that Papadopol (2000, 2001) proposes fall into four categories:

- Slowing deforestation and forest degradation;
- Expansion of existing carbon sinks through forest management;
- Creation of new carbon sinks through expansion of forest area, and;
- Substitution of fossil fuels with renewable wood-based fuels.

The objective of these mitigation measures is to attempt a gradual reversal of the effects caused by increased concentrations of GHGs, primarily through more effective carbon sequestration by forests. The mitigation measures are suggested ways to manipulate the carbon cycle through silvicultural means, and especially in the forest soil. These measures are particularly applicable to the latitudinal ranges of temperate and boreal forests in Canada and include the following (Papadopol 2000, 2001):

Reforesting Immediately After Harvest

This measure has three important aspects; the first is that forest coverage should be restored to all surfaces that were previously covered by forest as soon as possible to continue the carbon sequestration function. Priority needs to be given for species and silvicultural methods that will result in productive new forests, and that reforesting must be done to avoid soil exposure, soil organic matter decomposition, and to maintain a carbon sink.

Restoring the Productive Forest Cover

This refers to bare areas that have sustained and can sustain forest production so as to establish the CO_2 sink function and to arrest any erosion. On many of these sites, greater and more diversified efforts and investments may have to be made with respect to vegetation management. Many of the areas in this category will be in forest zones where harvesting has occurred, but for various reasons, regeneration did not succeed.

Expanding Existing Forest Carbon Sinks

This refers to areas where “high-grading” has occurred in the past and where carbon storage potential can be increased. Other considerations may include reforesting to arrest erosion, adding fertilizer to boost fertility, reforest marginal agricultural land, and retaining slash and other debris after logging operations. This measure may require establishment of plantations to assist migration of tree species into new ranges and may involve species not previously present. This measure may facilitate the movement of existing species northward or to higher elevations, as they are expected to do under climate change scenarios.

Establishing New Plantations

Plantations should be established on productive and suitable sites that will retain their economic objective and may replace low productivity forest vegetation on fertile soils. The plantations may use fast-growing genotypes such as poplars which will shorten rotations. On sites with high permeability, preference should be given for 1-2 rotations to pioneer species, especially for their role of soil organic buildup.

Shifting Species

Tree species will migrate at individual paces and not as entire ecosystems, and the rate of migration to new habitats will vary. Knowledge of genetic variability, though presently adequate only for a few commercially valuable conifers, may help to guide adaptive transfer under a changing climate.

Replacing Drought Sensitive Species

In areas prone to drought conditions it may be possible to consider planting more drought-resistant species. For example, the root systems of red pine and jack pine do not usually extend beyond 1.0 to 1.2 m and are therefore unable to tap into water stored at deeper levels. Suggested replacement species might include European larch, Douglas-fir and ponderosa pine.

Substituting Wood Fuels for Fossil Fuel

Short-rotation woody crops would have the greatest potential for this measure, such as *Populus* sp. and *Salix* sp. This measure may be applicable in most geographical zones and is the substitution of biomass energy, a renewable resource, for fossil fuel combustion.

Increasing Protection Measures

Conifer monocultures and extensive trembling aspen forests may be particularly vulnerable to outbreaks of major insect defoliator species (Hogg et al. 2002, 2005; Volney and Fleming 2000). Every effort should be made to ensure vigorous and healthy forest stands. Control measures may require silvicultural or pesticidal treatment measures for protection. Periodic thinning, removal of diseased or weakened trees and shorter rotation periods may also be considered. Tree breeding is also an option over long periods and may be desirable in that it may not force evolutionary resistance as can frequently occur with pesticides.

Increasing Fire Protective Measures

Increased risks of forest fires (frequency and extent) are predicted with climate change, requiring increased fire protection capacity to minimize economic losses, reduce release of CO_2 into the atmosphere, maintain forest cover on soils, and to allow existing CO_2 sinks to remain effective.

Establishing Surveillance Systems

Surveillance technology needs to be deployed to address forest health and productivity issues, monitor abiotic and biotic agents for their potential to cause tree and forest damages, and tree and stand responses to disturbance events. A main objective of surveillance activities in future years will likely be to minimize the loss of carbon from biomass to the atmosphere, and thus to identify prompt intervention strategies where possible.

Other suggested measures that relate to climate change issues might include the following:

Allocation of Annual Allowable Cuts

Allocation of annual allowable cuts (AAC) should take into account climate change risks such as catastrophic fire or insect disturbances on an area and species at risk basis (Hogg et al. 2005; Kurz et al. 2008; Volney and Fleming 2000).

Future Forest Pests and Increased Fire Disturbances

Future disturbances expected to occur in the coming decades will require the forest resource community to implement extensive changes to forest resource management policy, forestry operations and conservation planning. A high priority will be coping with and adapting to forest disturbance while maintaining the genetic diversity and resilience of forest ecosystems (Hamann et al. 2005).

Restoring Carbon Balance to Forests

Efforts that help to restore the carbon balance where natural forest disturbances have occurred can be applied through forest management and include increasing harvest rotation lengths, reducing regeneration delays, or increasing stocking densities. Similar disturbances may be caused by introduced invasive species (Kurz et al. 2008).

Encourage Uneven-aged Stand Management

The encouragement of uneven-aged stand management as opposed to clearcutting is suggested as a means to help mitigate anticipated effects of climate change and to sustain ecosystem function, especially in bark beetle (e.g., mountain pine beetle, spruce beetle) attack areas (BC Ministry of Forests and Range 2006).

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FIGURE 1: **Projected temperature increases for different scenarios, within the context of 1 000 years of historic record.**
Adapted from Climate Change Impacts and Adaptation: A Canadian Perspective, 2004.

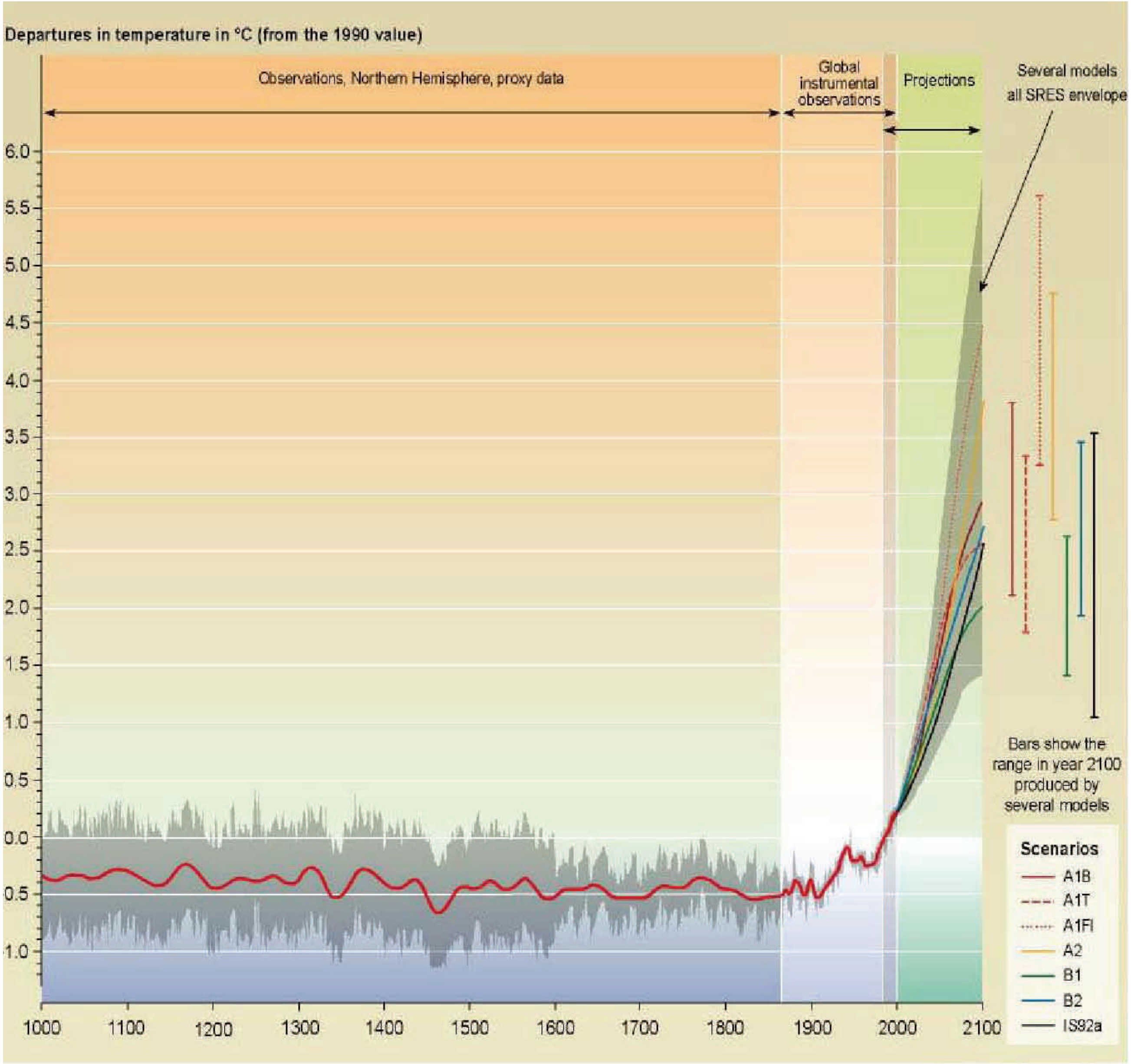


FIGURE 2: Trends in atmospheric CO_2, CH_4 and N_2O during the last 1 000 years .
Adapted from Climate Change Impacts and Adaptation: A Canadian Perspective, 2004.

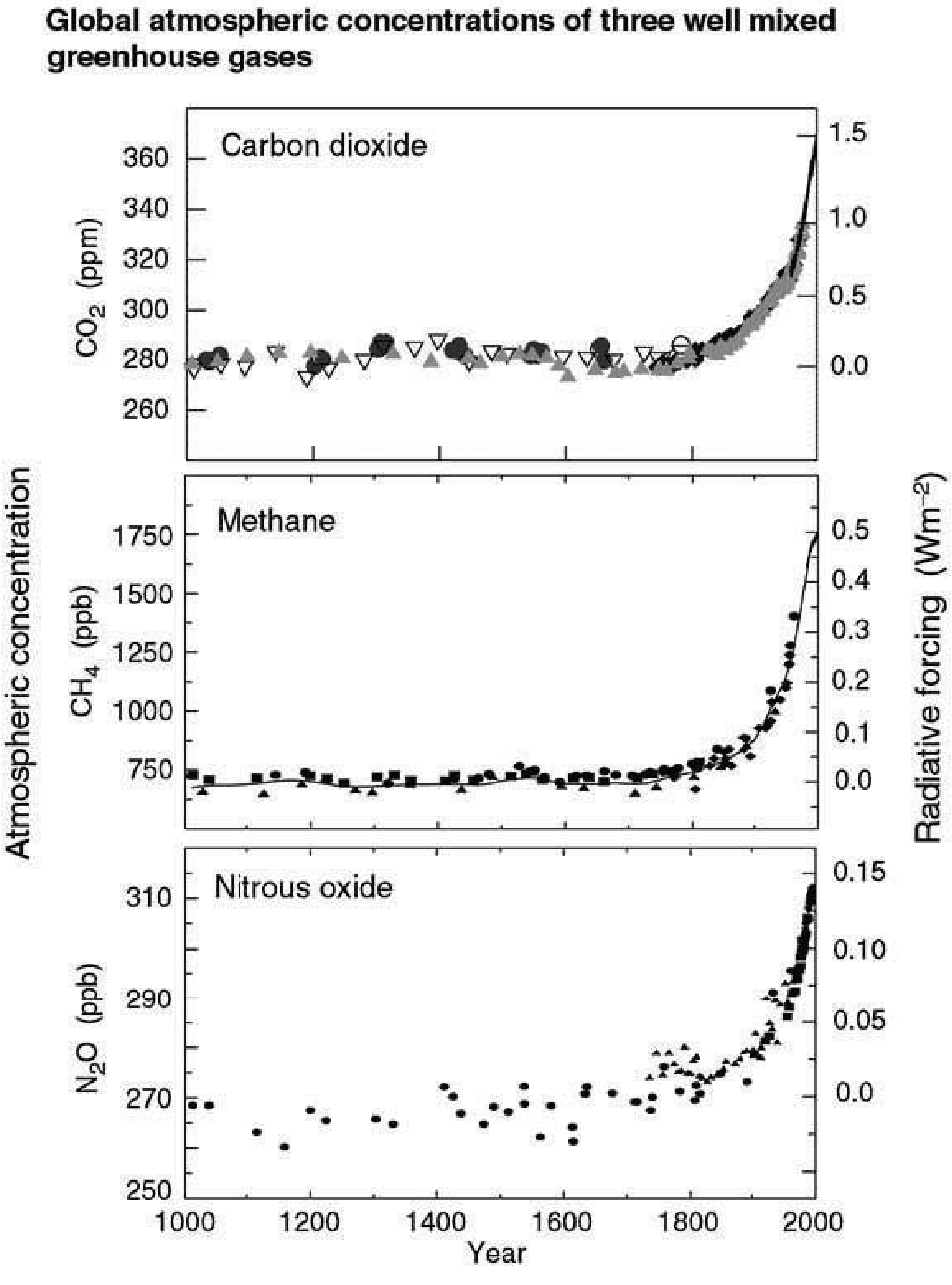


Fig. 3   AMT 1961-1990

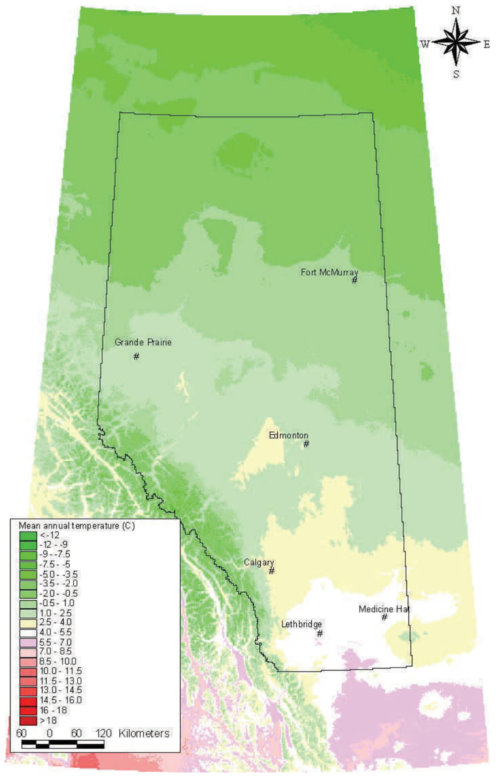


Fig. 4   AMT 2020s

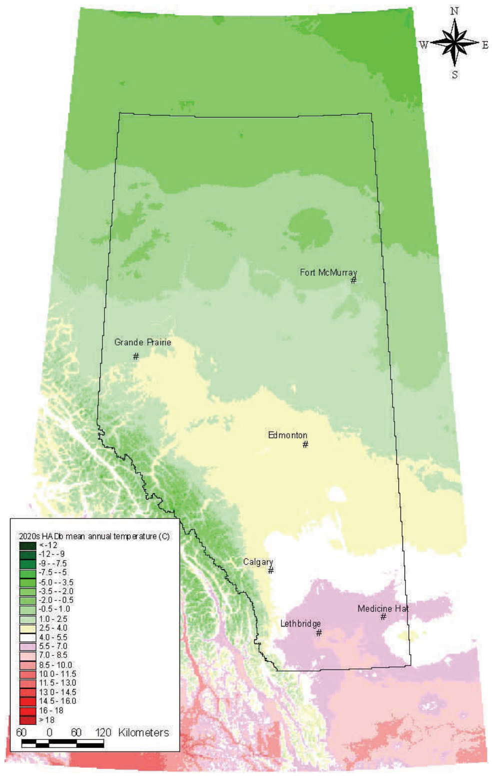
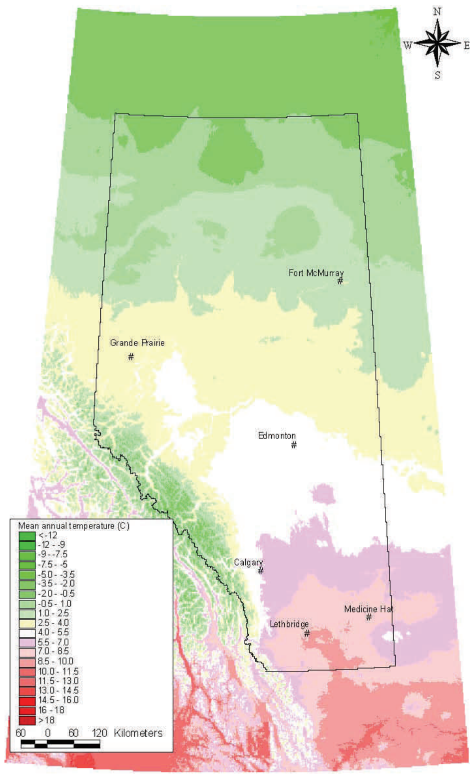


Fig. 5   AMT 2050s



Figures 3-5: Annual Mean Temperature °C (AMT) for the 1961-1990 baseline period (3); AMT for 2020’s scenario (4); and AMT for 2050’s scenario (5).
Adapted from Alberta Climate Model (Anon. 2005) as presented in E. Barrow and G.Yu (2005).

Fig. 6 AMP 1961-1990

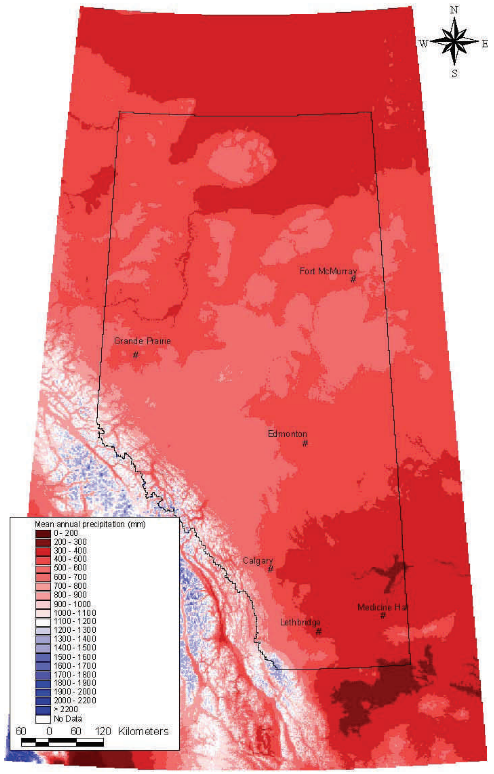


Fig. 7 AMP 2020s

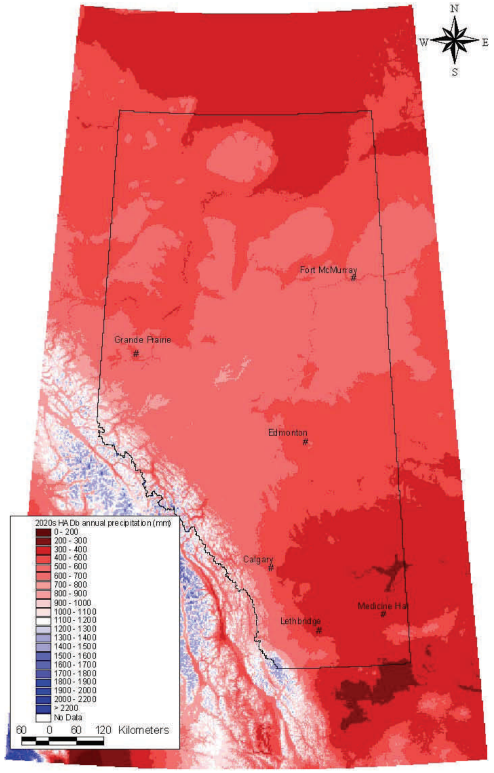
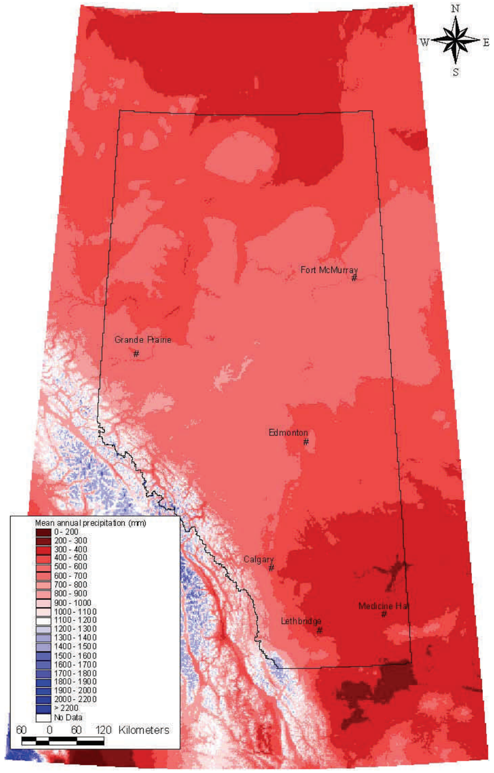


Fig. 8 AMP 2050s



Figures 6-8: Annual Mean Precipitation (AMP) for the 1961-1990 baseline period (6); AMP for 2020's scenario (7); AMP for the 2050's scenario (8).
Adapted from Alberta Climate Model (Anon. 2005) as presented in E. Barrow and G. Yu (2005).

Fig. 9 ADD 1961-1990

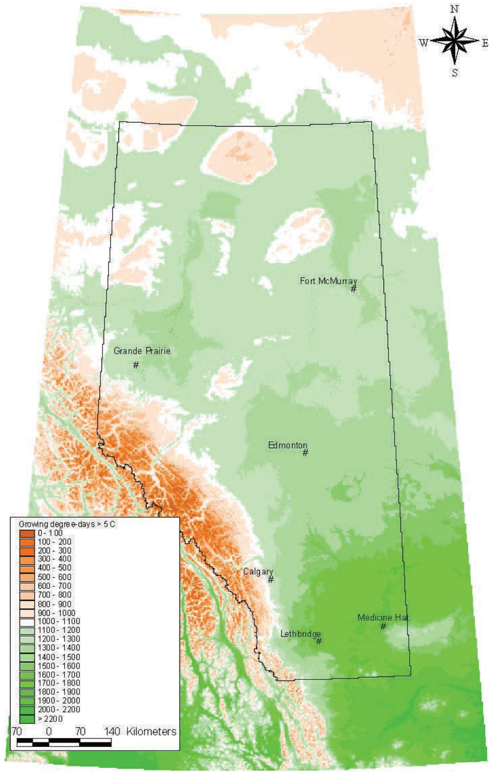


Fig. 10 ADD 2020s

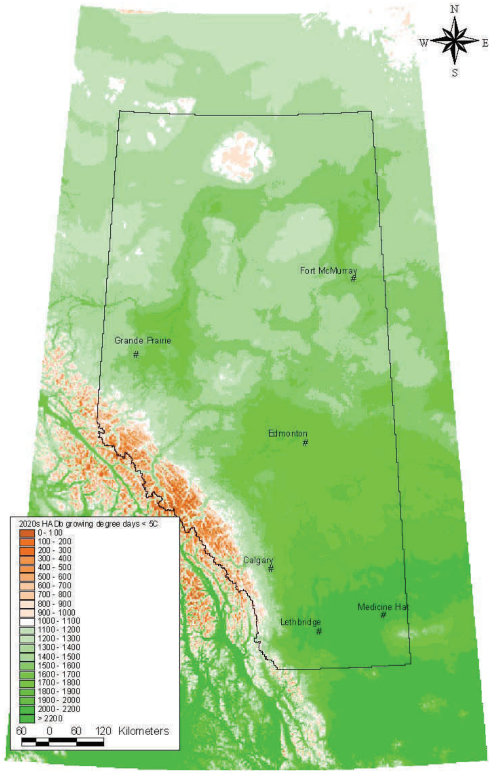
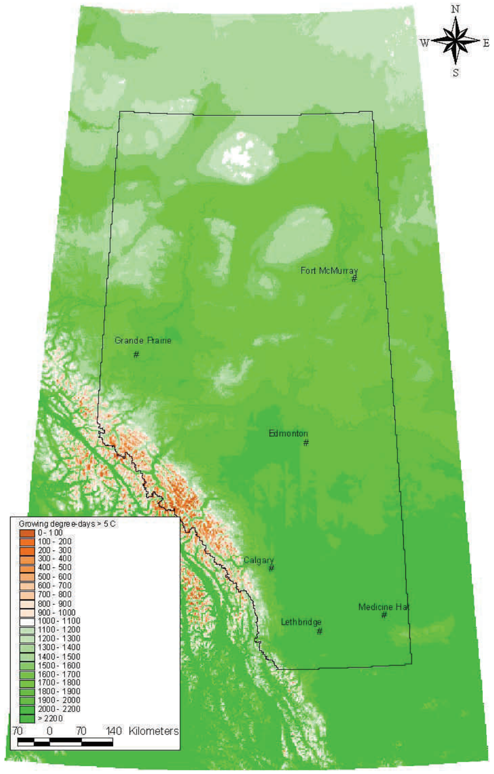


Fig. 11 ADD 2050s



Figures 9-11: Annual Degree Days >5°C (ADD) for the 1961-1990 baseline period(9); ADD for the 2020's scenario (10); ADD for the 2050's scenario (11).
Adapted from the Alberta Climate Model (Anon. 2005) as presented in E. Barrow and G.Yu (2005).

Fig. 12 AMI 1961-1990

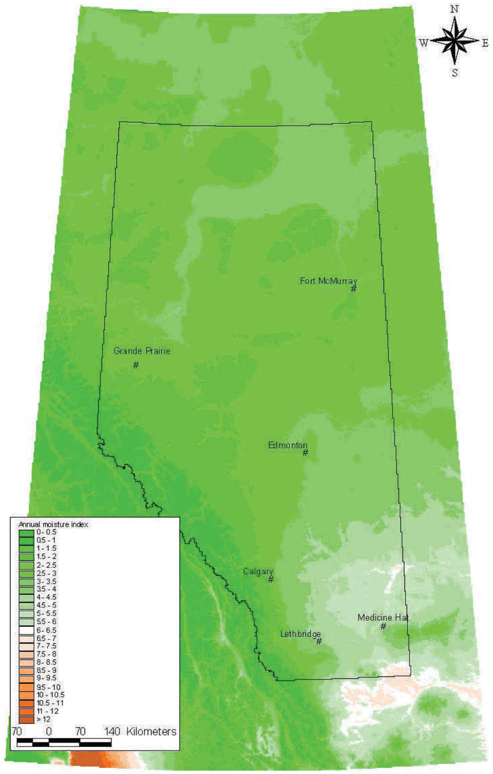


Fig. 13 AMI 2020s

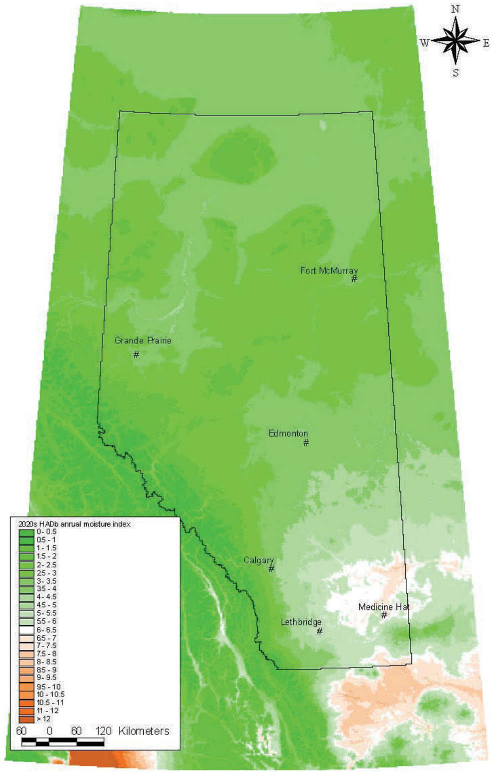
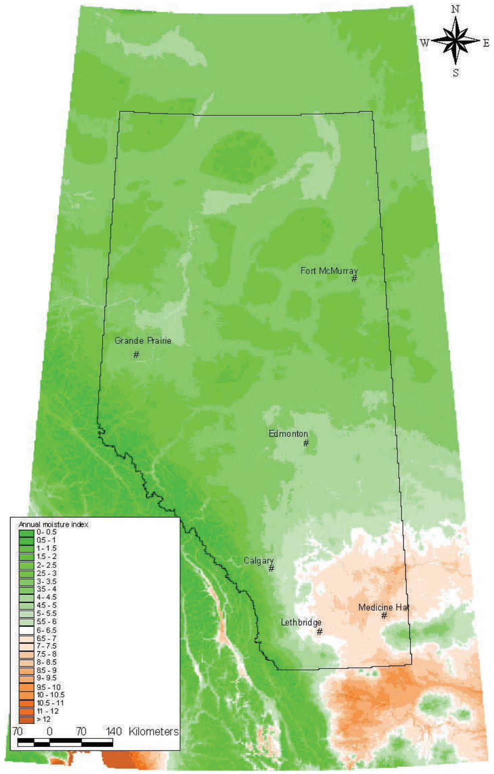


Fig. 14 AMI 2050s



Figures 12-14: Annual Moisture Index (AMI) for the 1961-1990 baseline period (12); AMI for the 2020's scenario (13); AMI for the 2050's scenario (14).
Adapted from Alberta Climate Model (Anon. 2005) as presented in E. Barrow and G.Yu (2005).

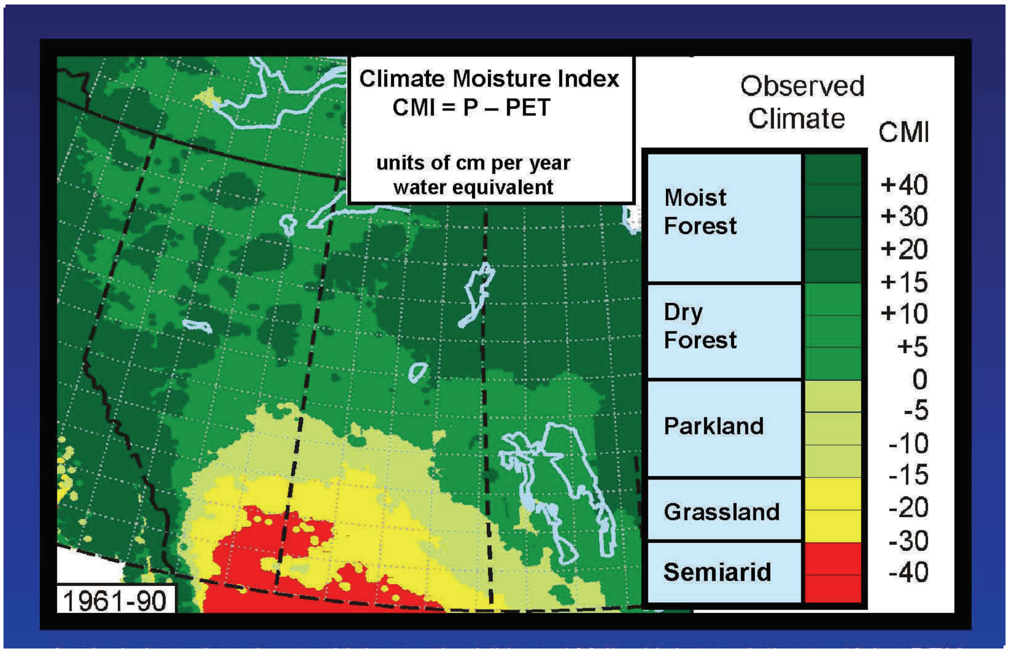


Figure 15 Present vegetation of the prairie provinces, based on the relationship with Climate Moisture Index (CMI) for the baseline period 1961-1990.
Adapted from E.H. Hogg et al. (2004): Canadian Prairie Drought Workshop.

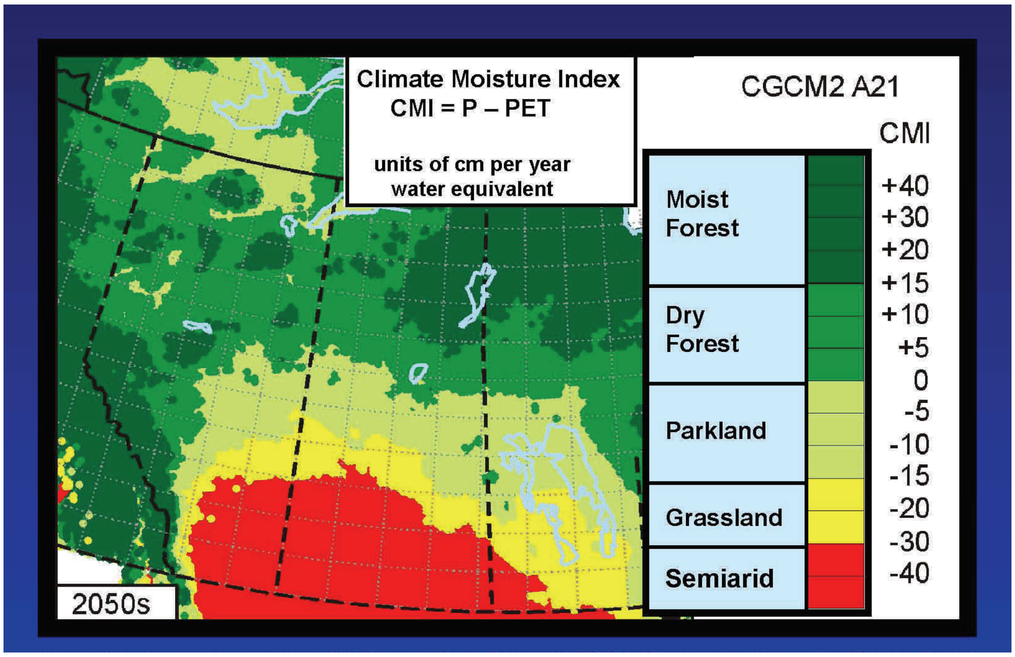


Figure 16 Present vegetation of the prairie provinces, based on the relationship with Climate Moisture Index (CMI) and projected to the 2050s.
Adapted from E.H. Hogg et al. (2004): Canadian Prairie Drought Workshop.

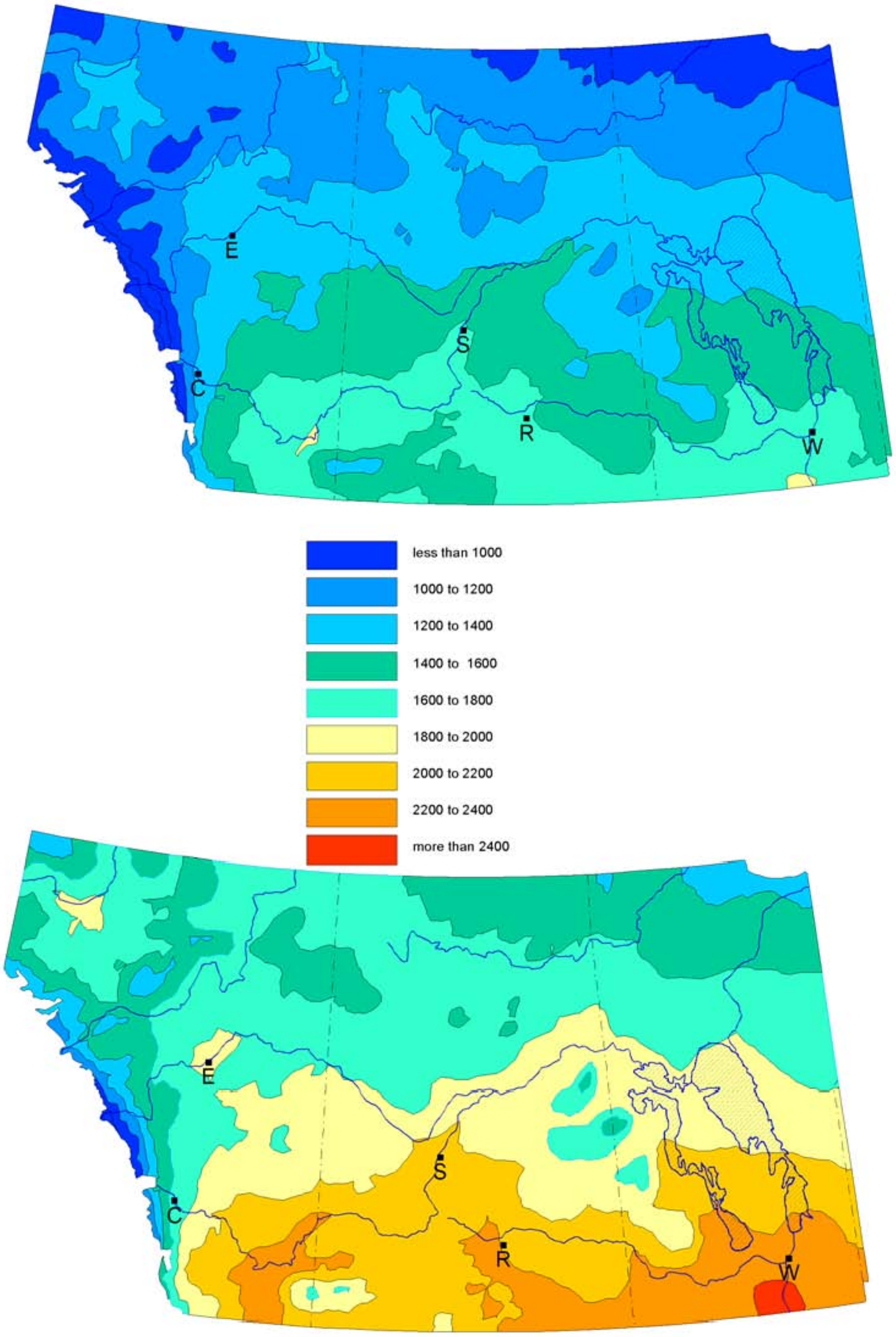


Figure 17 Growing degree-days (5° C base) for the study area, in the current climate (top) and in the CSIRO Mk2b B11 scenario for the 2050s (bottom).
Adapted from J. Thorpe et al. (2006): SRC Publication No. 11776-1E06.

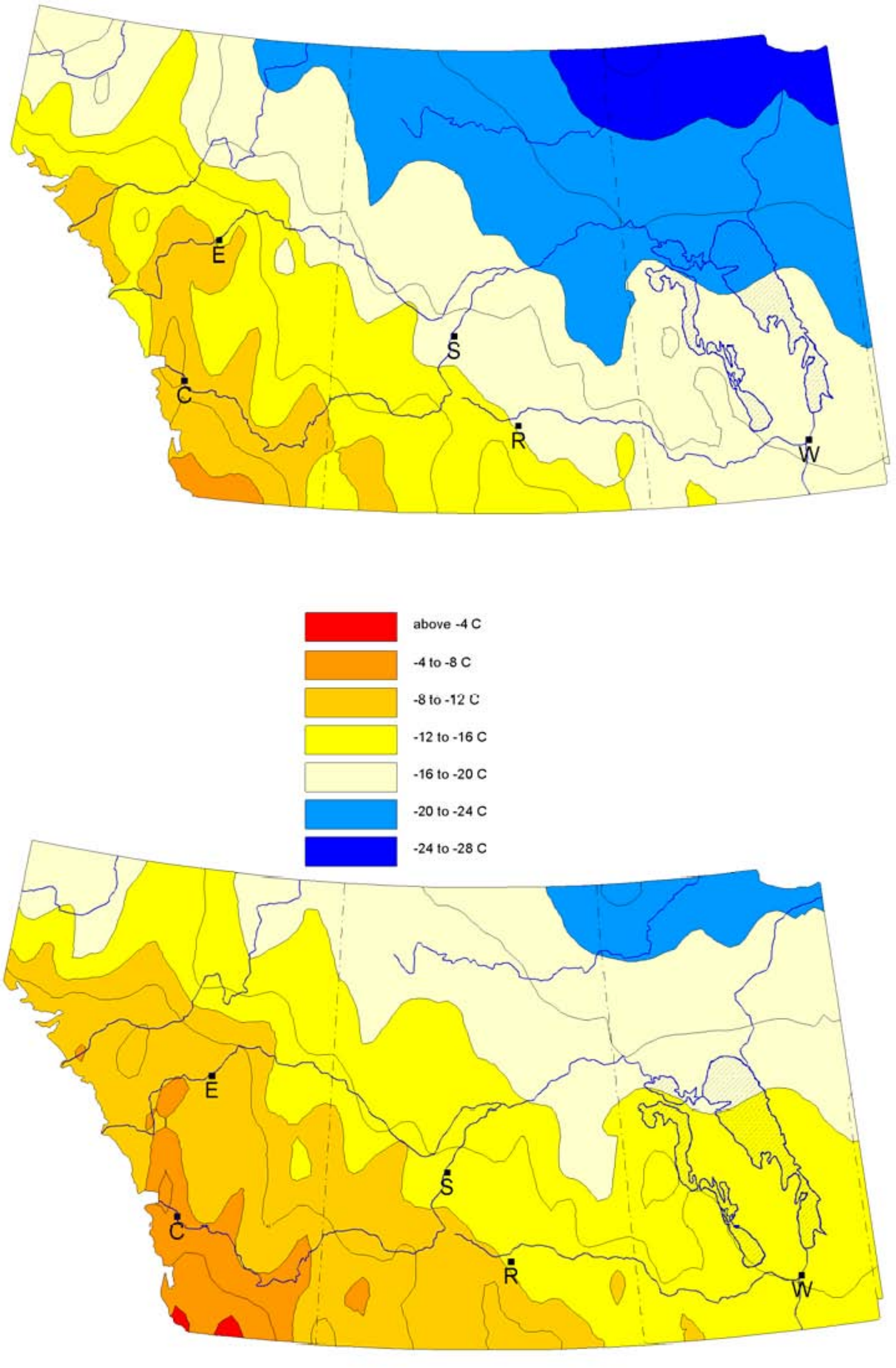


Figure 18 Mean temperature of the coldest month (° C) for the study area, in the current climate (top) and in the CSIRO Mk2b B11 scenario for the 2050s (bottom). Adapted from J. Thorpe et al. (2006): SRC Publication No. 11776-1E06.

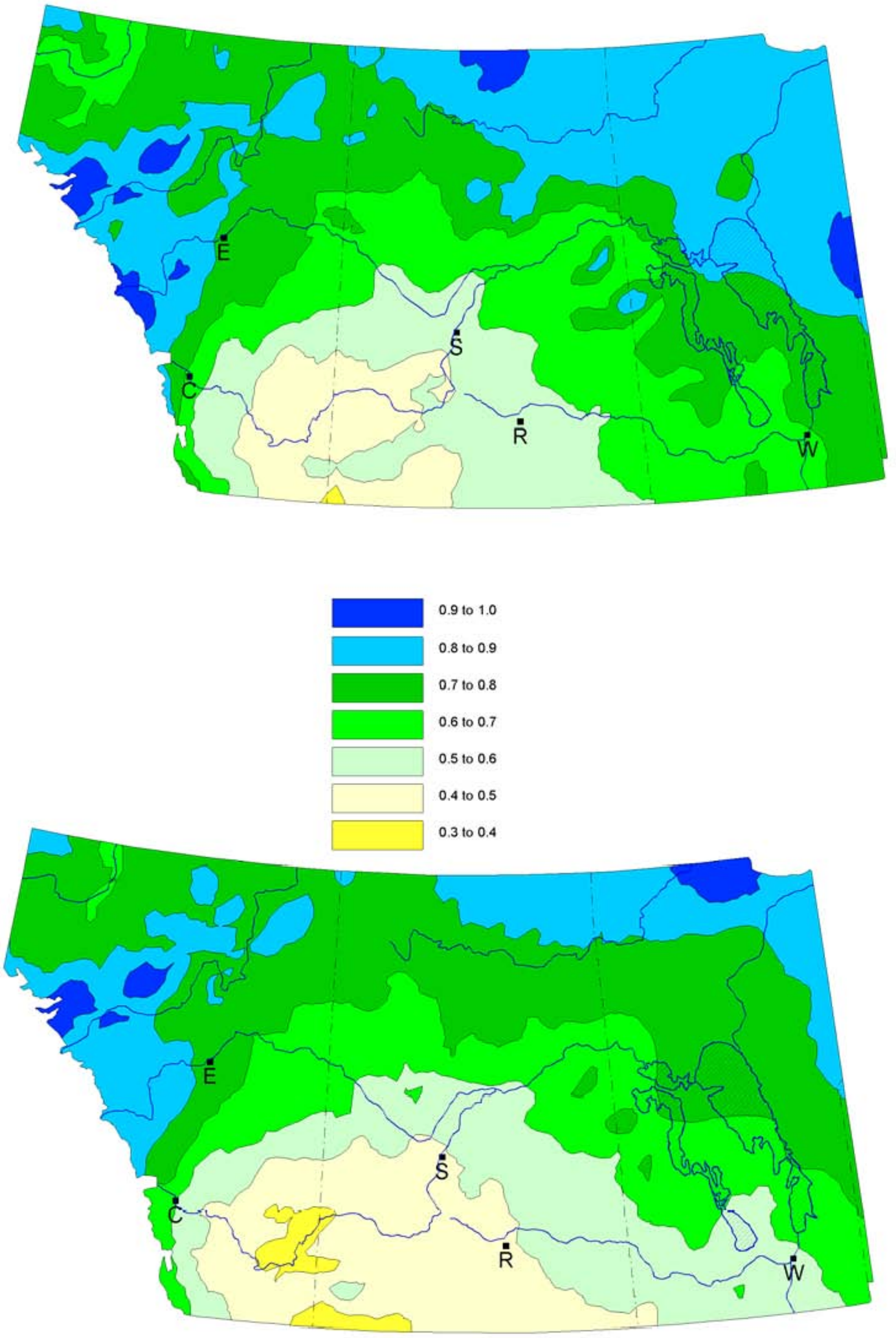


Figure 19 Moisture index (actual evapotranspiration divided by potential evapotranspiration) for the study area, in the current climate (top) and in the CSIRO Mk2b B11 scenario for the 2050s (bottom).
Adapted from J. Thorpe et al. (2006): SRC Publication No. 11776-1E06.

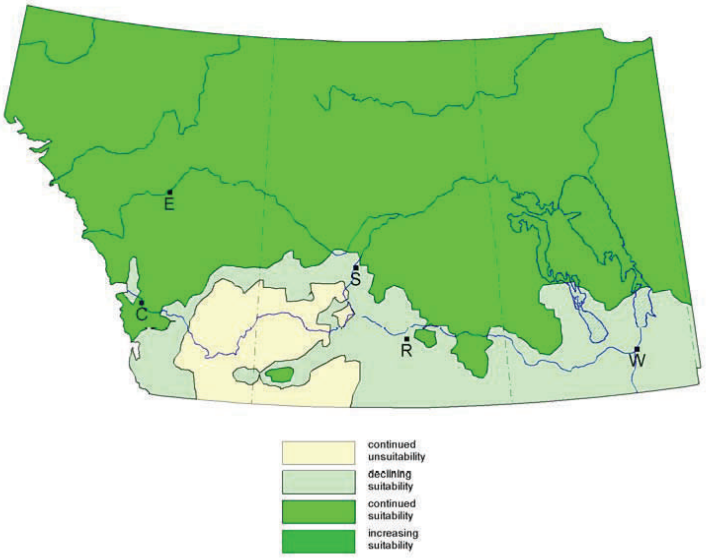


Figure 20 Changes in climatic suitability for trembling aspen from the current climate (1961-90 normals) to the CSIROMk2b B11 scenario for the 2050s.
Adapted from J. Thorpe et al. (2006): SRC Publication No. 11776-1E06

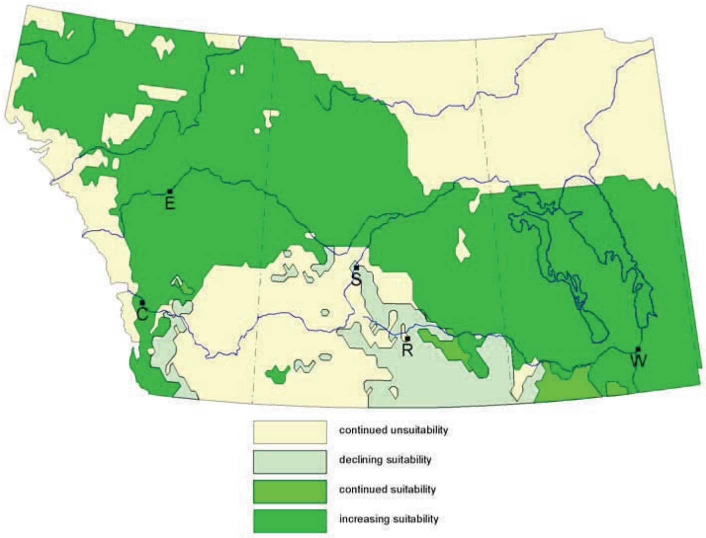


Figure 21 Changes in climatic suitability for Manitoba maple from the current climate (1961-90 normals) to the CSIROMk2b B11 scenario for the 2050s.
Adapted from J. Thorpe et al. (2006): SRC Publication No. 11776-1E06

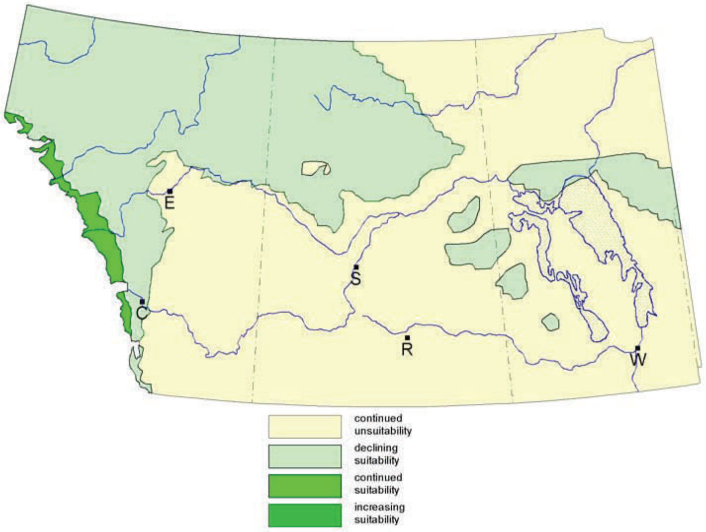


Figure 22 Changes in climatic suitability for lodgepole pine from the current climate (196190 normals) to the CSIROMk2b B11 scenario for the 2050s.
Adapted from J. Thorpe et al. (2006): SRC Publication No. 11776-1E06

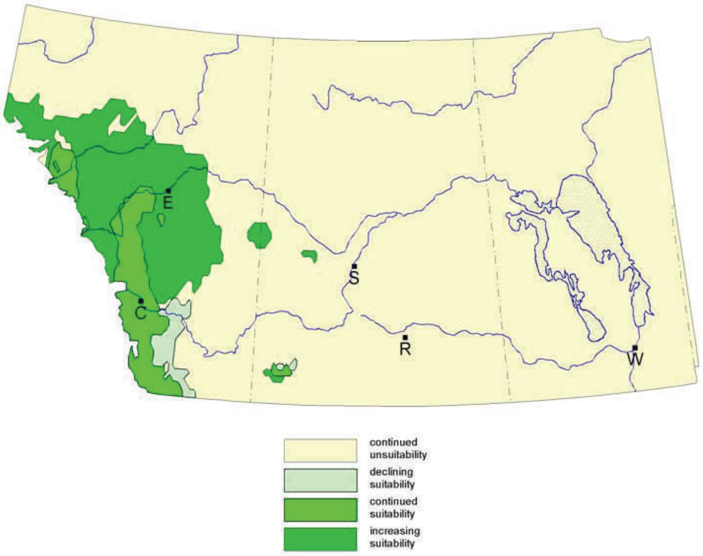


Figure 23 Changes in climatic suitability for Douglas-fir from the current climate (1961-90 normals) to the CSIROMk2b B11 scenario for the 2050s.
Adapted from J. Thorpe et al. (2006): SRC Publication No. 11776-1E06

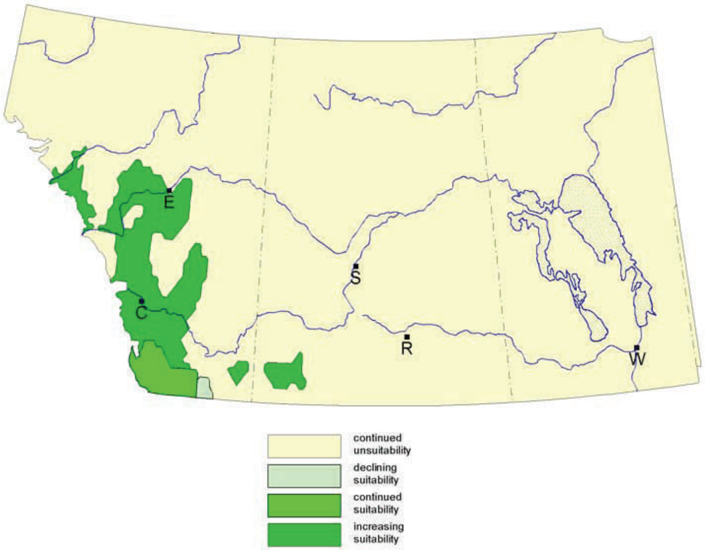


Figure 24 Changes in climatic suitability for ponderosa pine from the current climate (1961-90 normals) to the CSIROMk2b B11 scenario for the 2050s.
Adapted from J. Thorpe et al. (2006): SRC Publication No. 11776-1E06

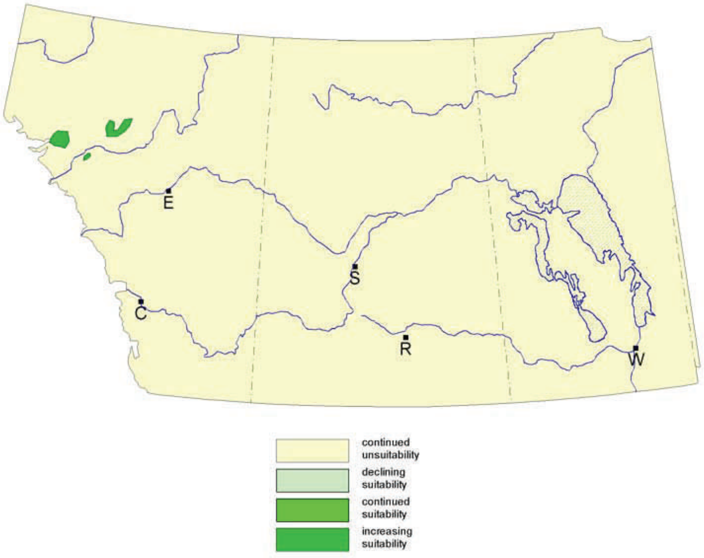


Figure 25 Changes in climatic suitability for red pine from the current climate (1961-90 normals) to the CSIROMk2b B11 scenario for the 2050s.
Adapted from J. Thorpe et al. (2006): SRC Publication No. 11776-1E06

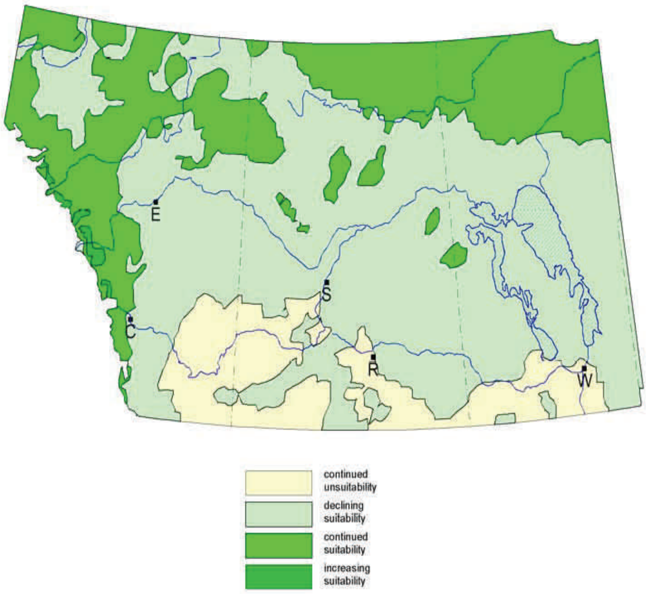


Figure 26 Changes in climatic suitability for Scots pine from the current climate (1961-90 normals) to the CSIROMk2b B11 scenario for the 2050s.
Adapted from J. Thorpe et al. (2006): SRC Publication No. 11776-1E06

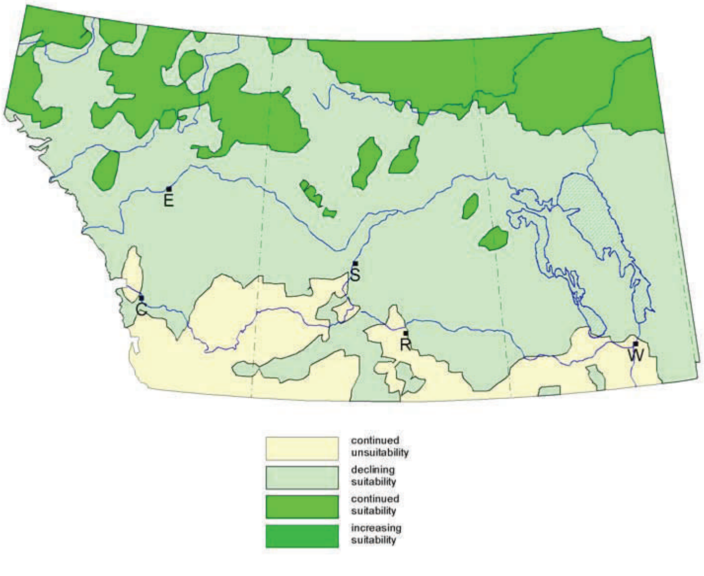
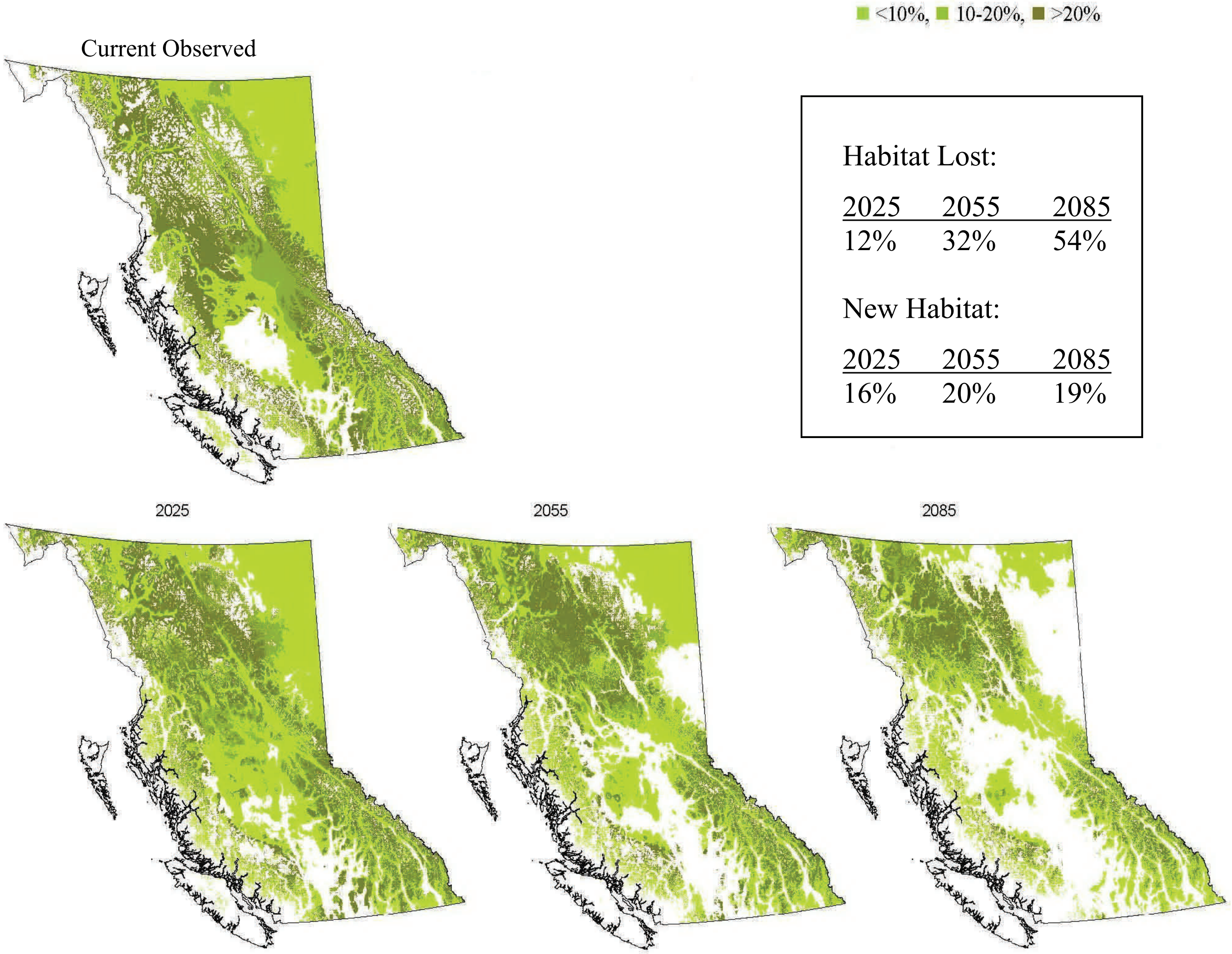


Figure 27 Changes in climatic suitability for Siberian larch from the current climate (196190 normals) to the CSIROMk2b B11 scenario for the 2050s.
Adapted from J. Thorpe et al. (2006): SRC Publication No. 11776-1E06

Figure 28 Current known range of Subalpine fir, *Abies lasiocarpa*, and predicted ranges for 2025, 2055 and 2085. Adapted from A. Hamann and T. Wang (2006).



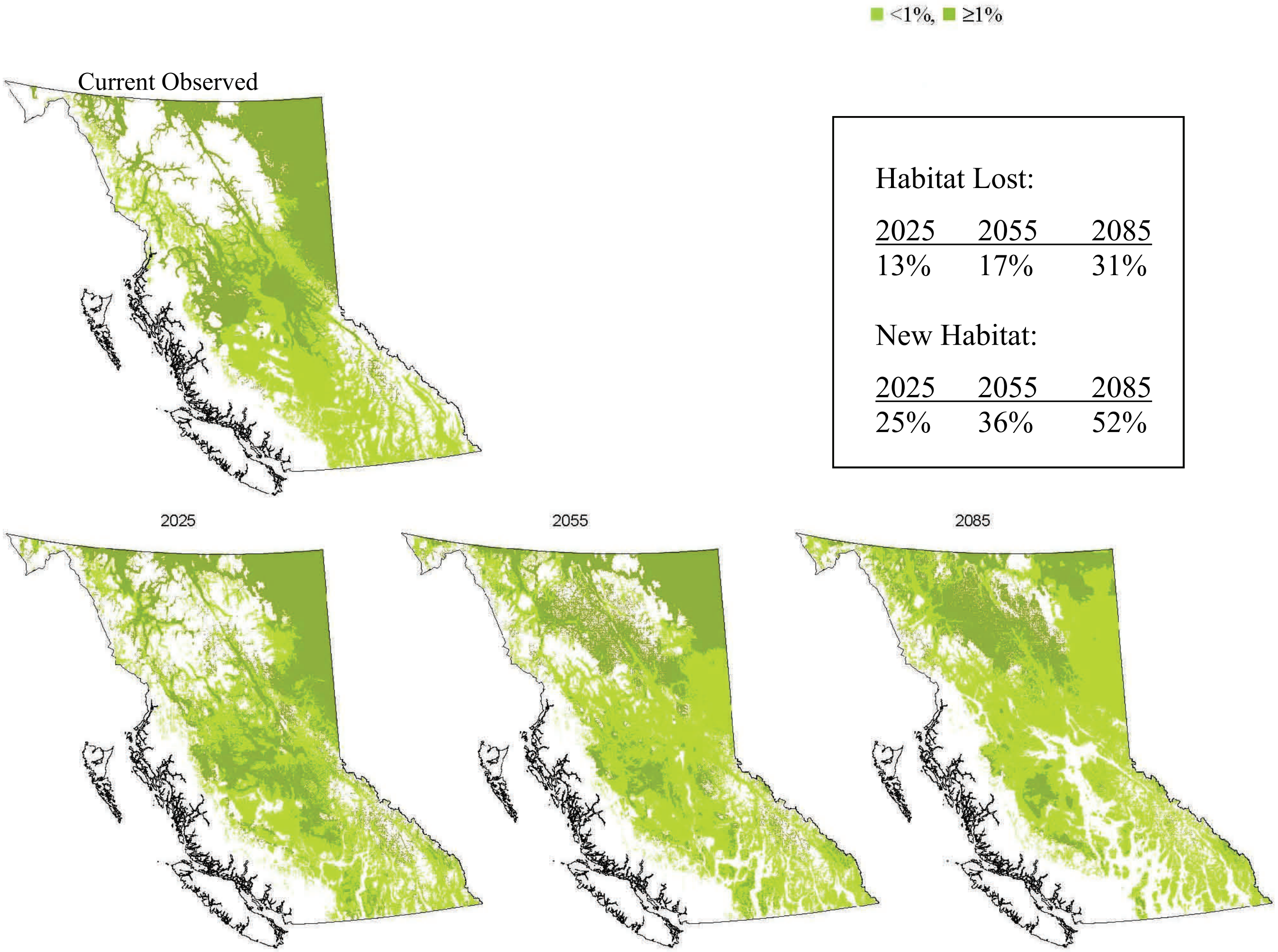
Habitat Lost:

2025	2055	2085
12%	32%	54%

New Habitat:

2025	2055	2085
16%	20%	19%

Figure 29 Current known range of Mountain alder, *Alnus tenuifolia*, and predicted ranges for 2025, 2055 and 2085. Adapted from A. Hamann and T. Wang (2006).



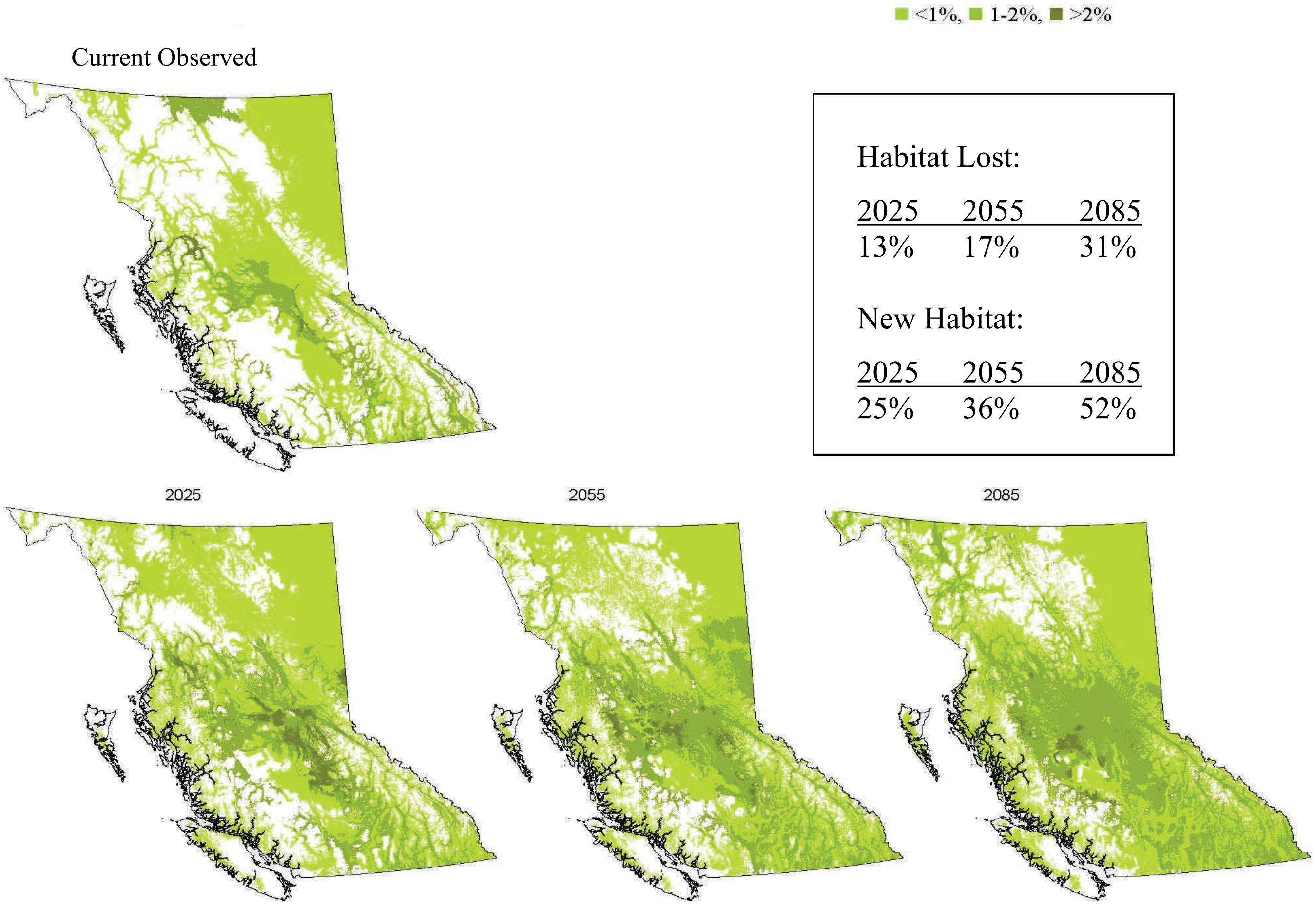
Habitat Lost:

2025	2055	2085
13%	17%	31%

New Habitat:

2025	2055	2085
25%	36%	52%

Figure 30 Current known range of Paper birch, *Betula papyrifera*, and predicted ranges for 2025, 2055 and 2085. Adapted from A Hamann and T. Wang (2006).



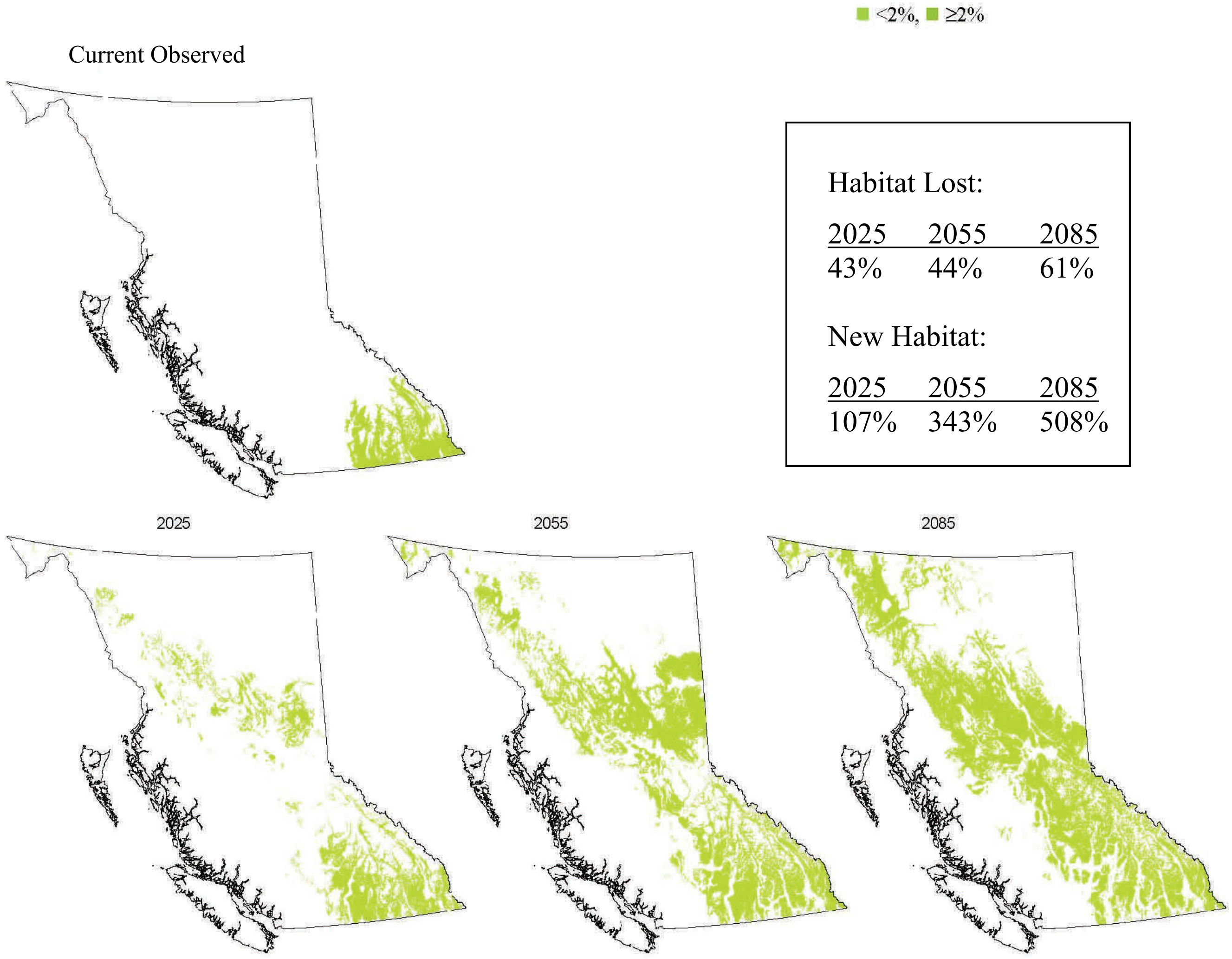
Habitat Lost:

2025	2055	2085
13%	17%	31%

New Habitat:

2025	2055	2085
25%	36%	52%

Figure 31 Current known range of Western larch, *Larix occidentalis*, and predicted ranges for 2025, 2055 and 2085. Adapted from A. Hamann and T. Wang (2006).



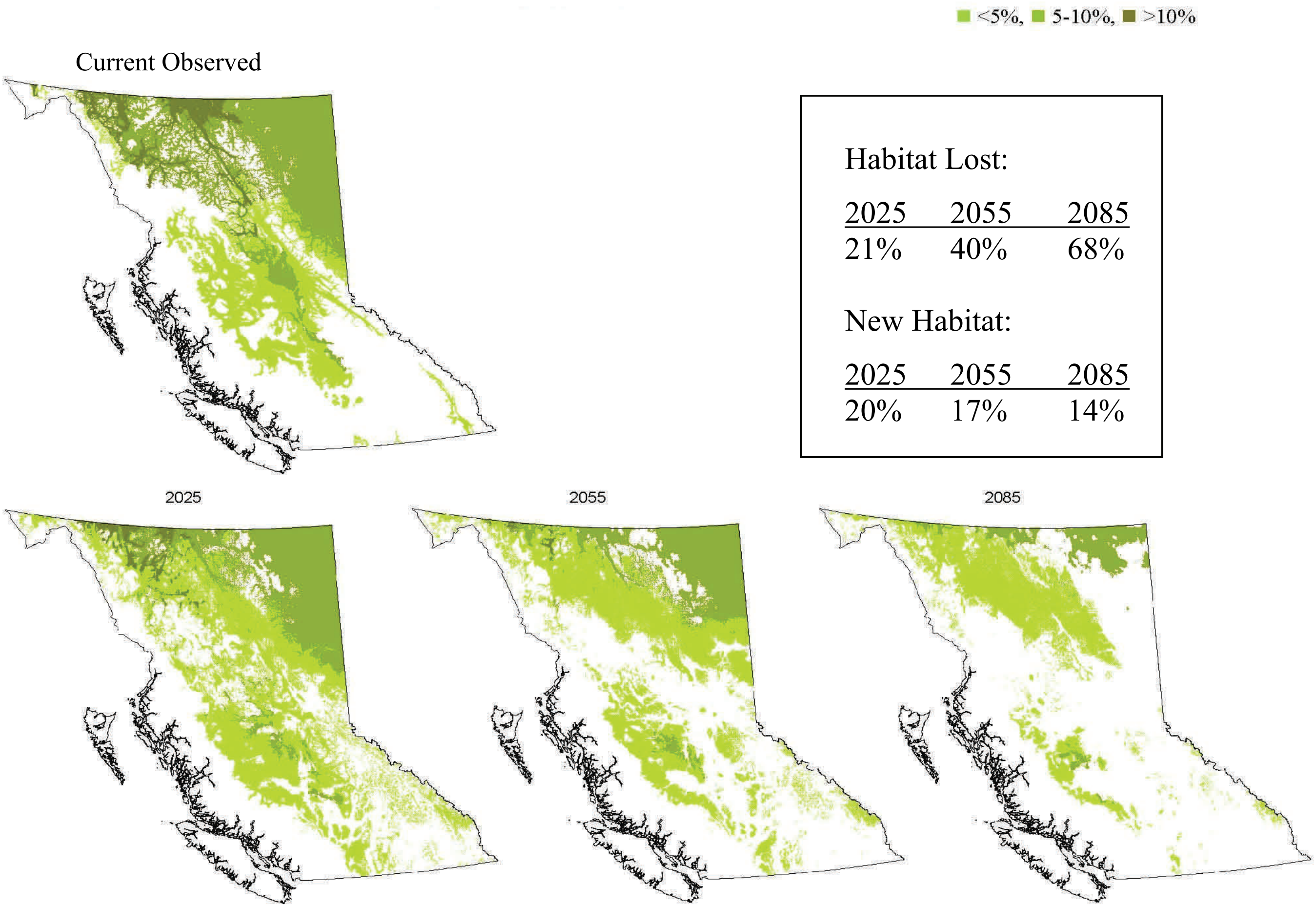
Habitat Lost:

2025	2055	2085
43%	44%	61%

New Habitat:

2025	2055	2085
107%	343%	508%

Figure 32 Current known range of White spruce, *Picea glauca*, and predicted ranges for 2025, 2055 and 2085. Adapted from A. Hamann and T. Wang (2006).



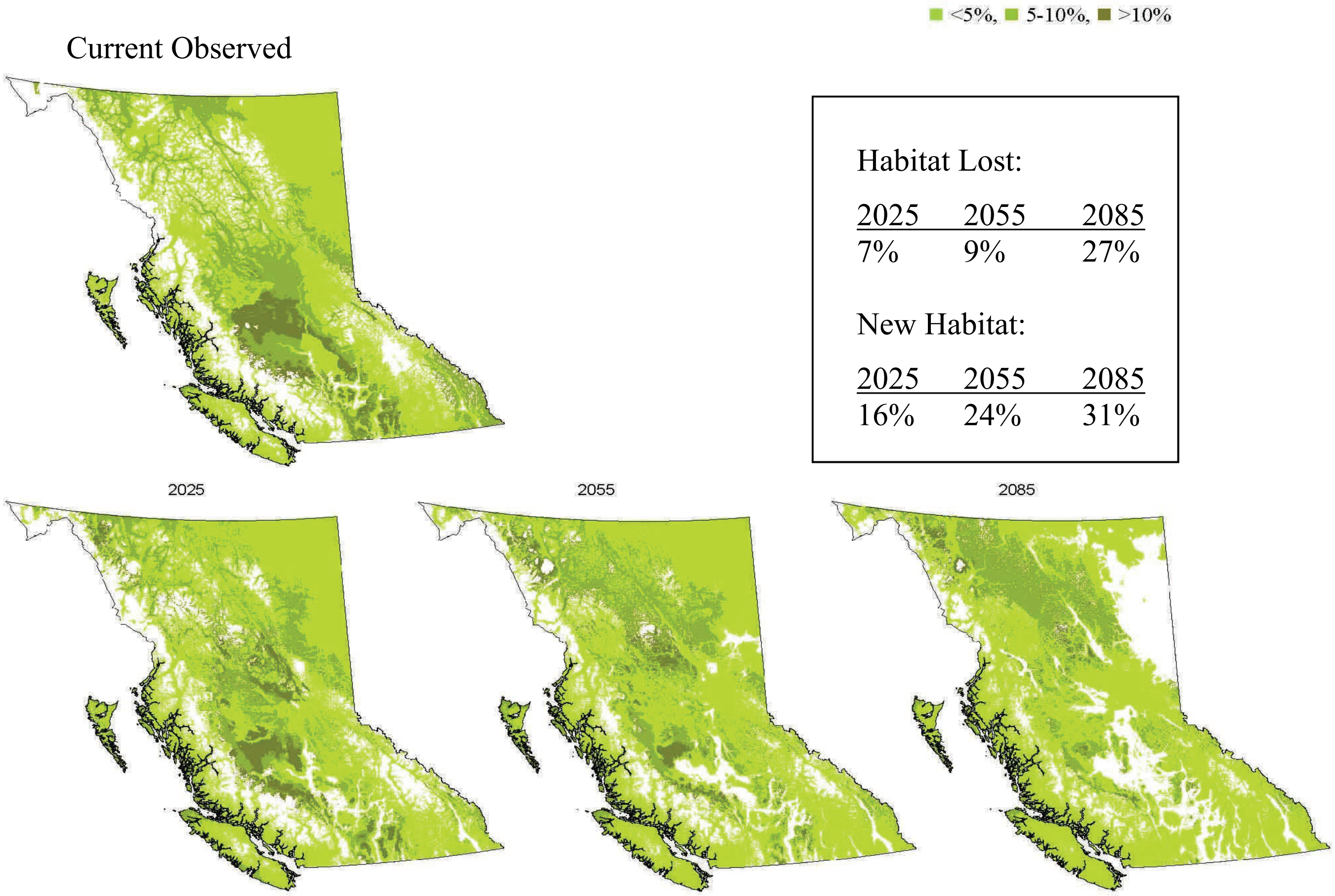
Habitat Lost:

2025	2055	2085
21%	40%	68%

New Habitat:

2025	2055	2085
20%	17%	14%

Figure 33 Current known range of Lodgepole pine, *Pinus contorta*, and predicted ranges for 2025, 2055 and 2085. Adapted from A Hamann and T. Wang (2006).



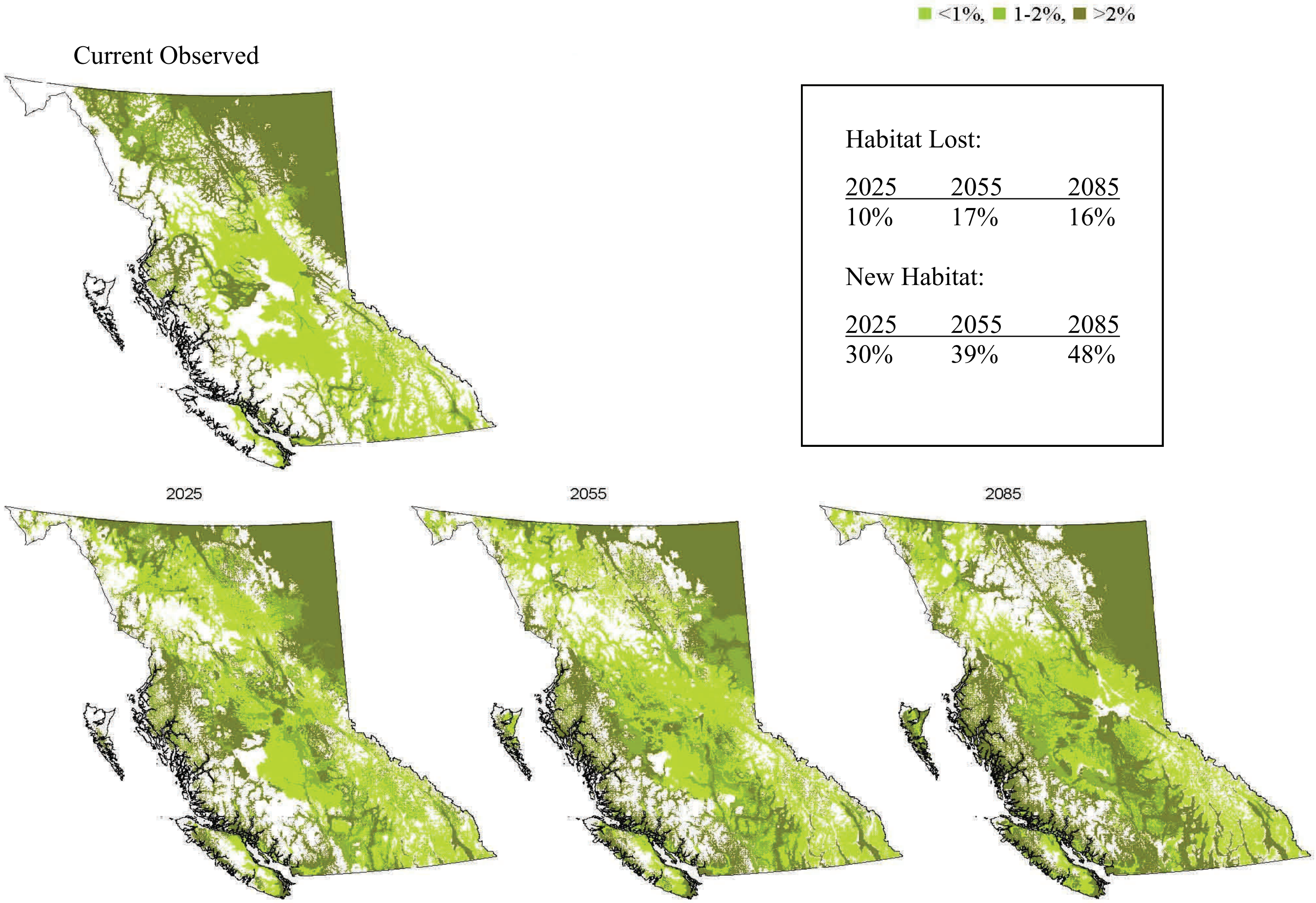
Habitat Lost:

2025	2055	2085
7%	9%	27%

New Habitat:

2025	2055	2085
16%	24%	31%

Figure 34 Current known range of Balsam poplar, *Populus balsamifera* L., and predicted ranges for 2025, 2055 and 2085. Adapted from A. Hamann and T. Wang (2006).



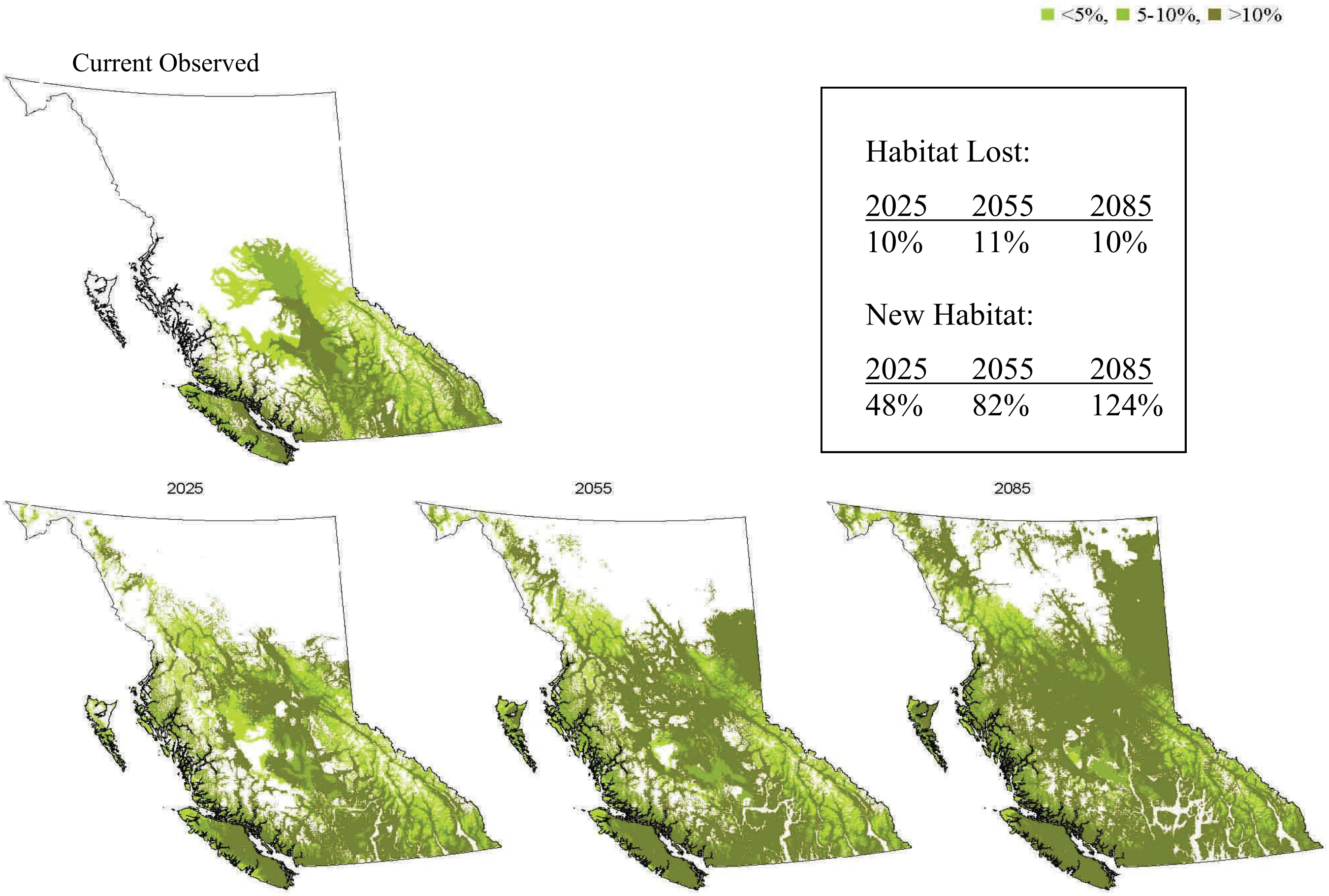
Habitat Lost:

2025	2055	2085
10%	17%	16%

New Habitat:

2025	2055	2085
30%	39%	48%

Figure 35 Current known range of Douglas fir, *Pseudotsuga menziesii*, and predicted ranges for 2025, 2055 and 2085. Adapted from A. Hamann and T. Wang (2006).



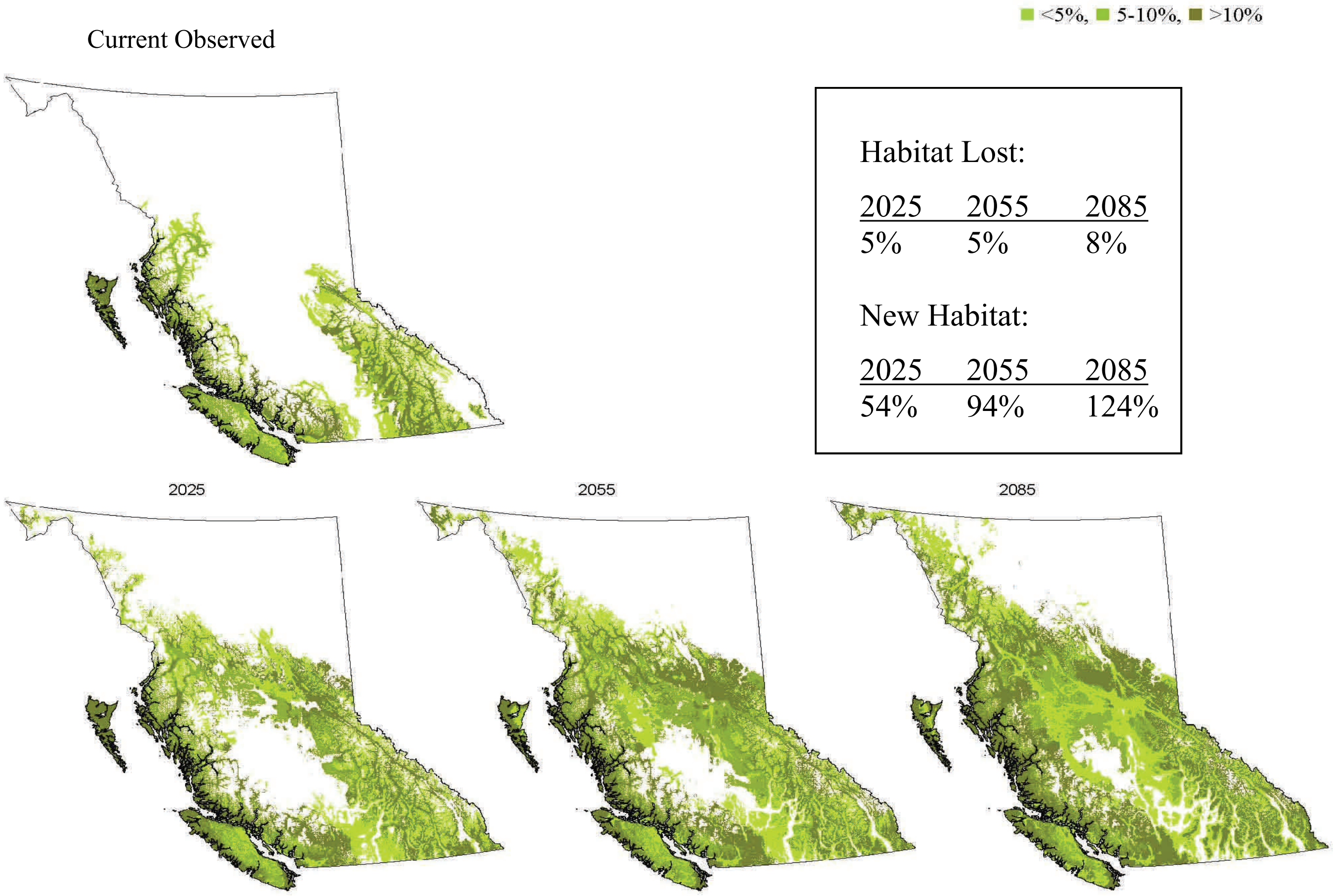
Habitat Lost:

2025	2055	2085
10%	11%	10%

New Habitat:

2025	2055	2085
48%	82%	124%

Figure 36 Current known range of Western red cedar, *Thuja plicata*, and predicted ranges for 2025, 2055 and 2085. Adapted from A. Hamann and T. Wang (2006).



Habitat Lost:

2025	2055	2085
5%	5%	8%

New Habitat:

2025	2055	2085
54%	94%	124%