Saskatchewan Research Council

LIMITED

Impacts of Climate Change on the Western Canadian Southern Boreal Forest Fringe

Prepared for
John Stadt
Alberta Sustainable Resource Development

By
Elaine Qualtiere
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Environment Division

SRC Publication No. 12855-3E11

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Executive Summary

Climate change is a pervasive and inescapable force that is already impacting Canada's forests and will continue to do so in the foreseeable future. The southern boreal forest fringe across the three Prairie Provinces of Canada (Alberta, Saskatchewan, and Manitoba) represents an area of specific concern with regards to climate change. This region is expected to be especially vulnerable to future impacts as it forms the prairie-boreal forest boundary, making it the first southern area of the forest to suffer and respond to climate change impacts.

Predicted climate change impacts on the southern boreal forest include increases in extent and frequency of droughts, fire, insect attack and disease. This in turn has the potential to cause increased tree mortality, species shifts, reduced productivity, decreased carbon sequestration, and difficulties in tree regeneration. These multiple sources of vulnerability will cause substantial changes in the environment, affecting ecosystems services and in turn impacting human society which depends upon the proper functioning of the forest for many goods and services. This region is especially vulnerable to climate change and many areas are unlikely able to retain tree cover in the future and should be at the forefront of adaptation initiatives in forest management.

This report reviews scientific documentation behind the vulnerabilities, risks, and potential adaptation options with regards to climate change across the southern boreal forest. Vulnerabilities to climate change must first be addressed before proper accounting of risk can be established. Once the extent of vulnerability is established, the risk of that effect occurring can then be taken into account and an assessment can be made with regard to each climate change impact. This will allow forest managers to determine whether an adaptation option is required.

Anticipatory and planned adaption can reduce potential negative impacts of climate change. Structured assessment frameworks like Alberta's Sustainable Resource Development vulnerability and adaptation framework can help determine areas of vulnerability to climate change, aid in identifying risks associated with each vulnerability and help in identifying possible adaptation options to help mitigate the full negative effects of a climate change event.

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Introduction

Forests cover more than a third of the Earth's land area. They regulate atmospheric gases, influence the hydrological cycle, and provide important ecosystem services to human populations, such as food, fiber and fuel. Forests can sequester carbon, which helps reduce the effects of global warming. They can improve water quality and quantity by lowering water temperatures, reducing runoff and erosion, and affecting the timing and amount of stream flow. Forests have recreational and cultural values, and provide 38,000 direct and indirect jobs related to the forest industry in Alberta (Alberta Sustainable Resource Development 2009b). In Saskatchewan, the forest industry employs approximately 6,000 people and pays about $215 million in annual wages and salaries. Another 7,600 Saskatchewan residents derive secondary employment from these activities (COSFI 2004) . Manitoba's primary forest products industry employs more than 3,400 workers which produce approximately $550 million per year (Manitoba Conservation 2010). Rising atmospheric CO_2, climate change, introduced species, and land cover modifications by humans are dramatically altering the distribution, biodiversity and biogeochemistry of forests (McMahon et al. 2009). This could ultimately have serious consequences for the forestry industry in Alberta, Saskatchewan, and Manitoba.

The purpose of this report is to provide a review of the vulnerabilities, risks, and adaptation options for a number of proposed climate change impacts on the southern edge of Canada's western boreal forest. Vulnerabilities and risks were established by Alberta Sustainable Resource Development (SRD) using the Climate Change Adaptation Framework developed by Deloitte and Touche. This review is structured to be consistent with the Deloitte & Touche framework, and is organized by the following main concepts: Vulnerability Assessments, Risk Assessments, and Adaptation Options (**Figure 1**).

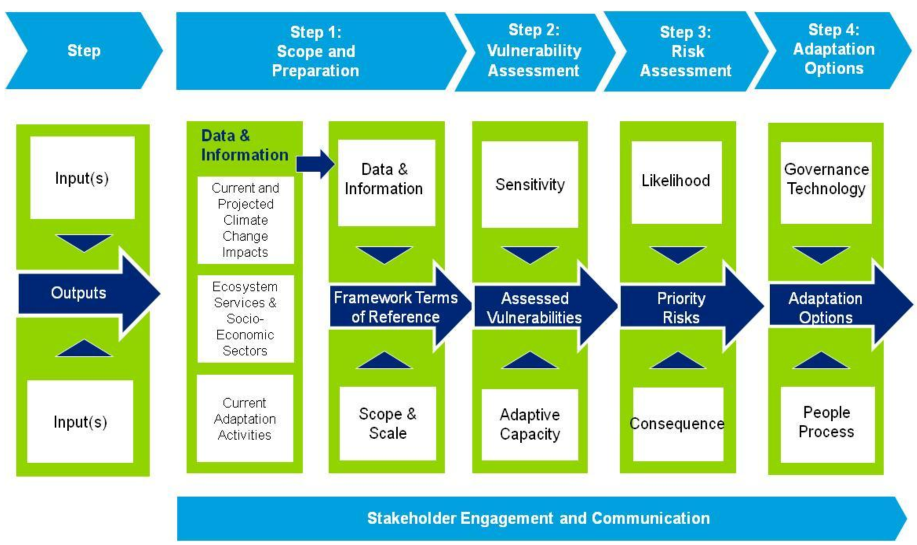

Figure 1: SRD' Climate Change Adaptation Framework developed by Deloitte & Touche. Inputs required in each step are described in the white boxes and the blue arrows describe the output of each step

The goal of this report is to provide information on the current knowledge surrounding sustainable use of forests and their ecosystem services under future climate change to aid in decision making.

SRD's Forest Management Branch identified a number of important ecosystem services provided by the western Southern Boreal Forest Fringe that directly affect forest management. These services and projected climate change impacts include: water regulation (increased tree mortality due to drought), habitat and landscapes (loss in forest ecosystems and habitats; shifts in forest biomes, increased fragmentation), pest regulation (increasing invasive species and loss of forest health), timber (increase in forest fire, regeneration failure, reduced tree growth), genetic resources (loss of species and genetic diversity), and carbon storage (declining forest productivity). Many of these services are broad and interrelated, often impacting forests as a combination of factors and rarely as a single focused event. Specific information on the boreal fringe will be given where available; however, many inferences regarding this region have made from scientific reviews that cover a more extensive landscape. It is important to recognize that many services generated by forest ecosystems provide essential support for human well-being (Bodin et al. 2006). Ecosystem services are essential to civilization, and operate on large scales in intricate ways that could not be replaced by technology (Daily et al. 1997) and will suffer modification or destruction under climate change. It has been noted in numerous studies that projected climatic changes during the 21st century will significantly impact forest ecosystems, the forest sector, and communities dependent upon them (Johnston et al. 2006).

Study Area

This report describes the implications of climate change for the southern **Boreal Plains** ecozone, including the **boreal transition**, **mid-boreal upland** and **interlake plain** ecoregions across Alberta, Saskatchewan and Manitoba. To the south lies the Prairie ecozone where its more northern ecoregion, the **Aspen Parkland**, abuts the Boreal Plains. The Aspen Parkland forms the southern tree-line in the western interior of Canada extending from central Alberta, all across central Saskatchewan to south central Manitoba (Campbell and Campbell 2000) and is climatically and ecologically a transition zone between boreal forests and grassland environments. North of the Boreal Plains is the Boreal Shield, the Taiga Plains, and the Taiga Shield. The Boreal Plains region lies in the middle of the three Prairie Provinces and is the focus of this report (**Figure 2**).

The Aspen Parkland Ecoregion

Increased moisture availability in the late summer and the distinct vegetation physiognomic structure distinguishes this area from adjoining ecoregions (Strong and Leggat 1981). This area is characterized by groves of aspen poplars and spruce interspersed in prairie grassland and it is estimated that less than 10 percent of the natural habitat in this region remains intact (World Wildlife Fund 2008). Most of the area has been converted to cropland or rangeland for grazing. A wide variety of crops are produced in this region including spring wheat and other cereals, oilseeds, as well as forages and several specialty crops (Environment Canada 1995). This region represents some of the most fertile and productive land in the Prairies. The forested area in this region is dominated by trembling aspen (*Populus tremuloides*), with secondary quantities of balsam poplar (*Populus balsamifera*), together with an understory of mixed herbs and tall shrubs. White spruce (*Picea glauca*) and balsam fir (*Abies balsamea*) are the climax species, but are not well represented because of more frequent fires. Other species of trees occur on scattered sandy soils deposits, including jack pine (*Pinus banksiana*), lodgepole pine (*Pinus controta*), white spruce, and black spruce (*Picea mariana*). The population in this ecoregion is approximately 1,689,000 (Environment Canada 1995) and this represents the highest amount of human inhabitants out of all the ecoregions discussed in this report. This area will not be extensively reviewed in this report, but it is important to note because of its proximity to the Boreal Plains.

The Boreal Plains Ecozone

The Boreal Plains are found in central Alberta, extend east through the center of Saskatchewan and slightly south of central Manitoba, covering 650,000 square kilometers. This region is characterized by a continental, relatively humid climate, with cold winters and moderately warm summers. It forms a transition zone between the prairie grasslands and the boreal forest, and is characterized by a discontinuous forest cover of groves and small stands in moister areas (Natural Resources Canada 2007b). White spruce and balsam fir are the potential climax species on mesic sites. Jack pine communities are common on sandy parent material such as outwash or sand dunes. Poorly drained sites are dominated by an overstory of black spruce with an understory of Labrador tea, cowberry, and mosses (Moss 1953). White birch (*Betula papyrifera*), trembling aspen and balsam poplar are also very common, particularly in the southern area of the boreal forest. Presently, agriculture is common along the southern fringes of the Boreal Plains, while forestry operations are scattered throughout this area (Strong and Leggat 1981). Three ecoregions are found along the southern edge of the Boreal Plains ecozone: the boreal transition, the mid-boreal uplands and the interlake plain. These three areas comprise the area of interest for this report, and are summarized in the following paragraphs from the Ecological Framework of Canada's website.

The Boreal Transition: This ecoregion extends from central Alberta to southern Manitoba and marks the southern limit of closed boreal forest and northern advance of arable agriculture. It is a dominantly deciduous boreal forest, characterized by a mix of forest and farmland. The predominant vegetation in this area is a closed cover of trembling aspen with balsam poplar as a secondary species. White spruce and balsam fir are the climate species but are not well represented due to fire. Poorly drained sites are often covered with sedges, willow, some black spruce and tamarack (*Larix laricina*). This region provides habitat for many wildlife species and migrant birds and waterfowl. Over 70% of the ecoregion is farmland, while other land uses include forestry, hunting, fishing, and recreation. The population in this ecoregion is approximately 300,000 people (Environment Canada 2010).

The Mid-Boreal Uplands: The mid-boreal ecoregion stretches from north-central Alberta to southwestern Manitoba, and occurs as 10 separate, mostly upland areas. These uplands form part of the continuous mid-boreal mixed coniferous and deciduous forest extending from northwestern Ontario to the foothills of the Rocky Mountains. This region is occupied by trembling aspen, balsam poplar, white and black spruce, and balsam fir. Deciduous stands have a diverse understory of shrubs and herbs; coniferous stands tend to promote feathermoss. Cold and poorly drained fens and bogs are covered with tamarack and black spruce. Permafrost is rare and found only in peatlands. Pulpwood and local sawlog forestry, water-oriented recreation, hunting, and trapping are the main land use activities. Agricultural activities are significant in southern parts of the ecoregion, particularly in Saskatchewan and Manitoba. The population of this ecoregion is approximately 45,000 people (Environment Canada 2010).

The Interlake Plain: This ecoregion extends northwest from the southeastern corner of Manitoba to the Saskatchewan boundary north of the Porcupine Hills. This region is dominantly deciduous boreal forest interspersed with farmlands and marks the southern limit of closed boreal forest and northern extent of arable agriculture in much of Manitoba. Native vegetation includes trembling aspen and balsam poplar, with white spruce and balsam fir as climax species. Open stands of jack pine occur on dry, sandy sites, while depressions are water-filled or covered with sedges, willow, some black spruce and tamarack. Around 40% of this area is farmland with a population of 85,000 people (Environment Canada 2010).

One unique landform within the Boreal Plain requires mention due to its importance in relation to climate change; these are the Island Forests that run along the southern extent of the boreal forest. These Island Forests represent the southernmost extreme of the boreal forest. These are unique forest communities created by windblown deposits that owe their existence to past glaciations events. They are slightly higher than the surrounding landscape and therefore intercept sufficient moisture to support tree growth (Henderson et al. 2002). They are characterized by high water tables and low near-surface soil moisture that result from the rapid infiltration of moisture down through the sand (Henderson et al. 2010). This infiltration shifts the competitive advantage away from grasses to deeper-rooted shrubs and trees. These exceptional landscapes, sustain refugia of trees isolated in a sea of grass or agriculture. They have remained forested while the surrounding lands have been cleared and farmed because of low agricultural suitability (Johnston et al. 2008). Their sandy soils, in combination with a semi-arid climate, result in frequent droughts which will likely increase in a warmer, drier future (Hogg and Bernier 2005) and increase the vulnerability of these last remaining vestiges of forests to climate change. The transition from forest to grassland in this region is linked to the climatic moisture balance, and the Island Forests are close to the threshold at which moisture becomes insufficient to support continuous forest vegetation (Johnston et al. 2008). This can be illustrated using Hogg's (1994) **Climatic Moisture Index (CMI)** which was mapped across the prairie provinces. The CMI is calculated as annual precipitation minus annual potential evapotranspiration, of which a zero value of this index almost exactly aligns with the southern boundary of the boreal forest

Climate Moisture Index (CMI): *The expected loss of water vapour from the landscape under well-watered conditions. A negative CMI denotes dry conditions typical of the aspen parkland or grassland regions, whereas positive values indicate levels of moisture commonly associated with the boreal forest.*

CMI = P – PET; P= annual precipitation; PET = annual potential evapotranspiration (Hogg et al. 2002a) across Alberta, Saskatchewan, and Manitoba. Therefore, positive index values support continuous forest cover while negative values support grassland/aspen parkland vegetation (Hogg 1994). The Elk Island National Park (**Box 1**), approximately 30 km east of Edmonton, would fall roughly along the 0 CMI value, indicating that in most years, precipitation is roughly balanced by potential evapotranspiration. This Island Forest is climatically on the brink of existence, representing the furthest extent of the boreal forest boundary and exists in the Aspen Parkland ecoregion. The lower CMI values for the Island Forests relative to the main boreal forest indicate that they should show the effects of climate change earlier than the main boreal forest. Climate change modeling has shown that the warming predicted over the coming century could shift the grassland/forest threshold northward, making the southern edge of the forest more suitable for aspen parkland vegetation (Hogg and Hurdle 1995) and putting significant stress on current Island Forest regions. The Island Forests in Alberta, Saskatchewan, and Manitoba are close to urban centers, surrounded by agriculture, and are the focus of an array of overlapping land uses: timber harvesting, wildlife habitat, livestock grazing, industrial developments, outdoor recreation and cultural values. A shift from forest cover to grassland as predicted by many studies (Hogg and Hurdle 1995, Allen and Breshears 1998, Camill and Clark 2000, Chapin III et al. 2004, Parmesan 2006a, McKenney et al. 2007, Olsson 2009, Michaelian et al. 2010) would drastically affect many of these land uses. The Island Forests' importance is increased when they are considered as an "early warning system" for the impacts of climate change on the larger boreal forest. Because they are at the dry southern margin, they should be the first areas to undergo change (Johnston et al. 2008) and will likely require adaptation measures to ensure their existence. These regions are also at risk due to increasing droughts, fire, insect attack, low genetic variability, invasive species, and anthropogenic land uses, which will eventually isolate remaining natural habitats currently protected in parks and reserves. If these unique landscapes are to be kept intact, adaptive management measures will be to be adopted in these regions soon. These regions offer up a perfect area in which we can begin implementing adaptation measures at a smaller scale before attempting larger initiatives in the main boreal forest.

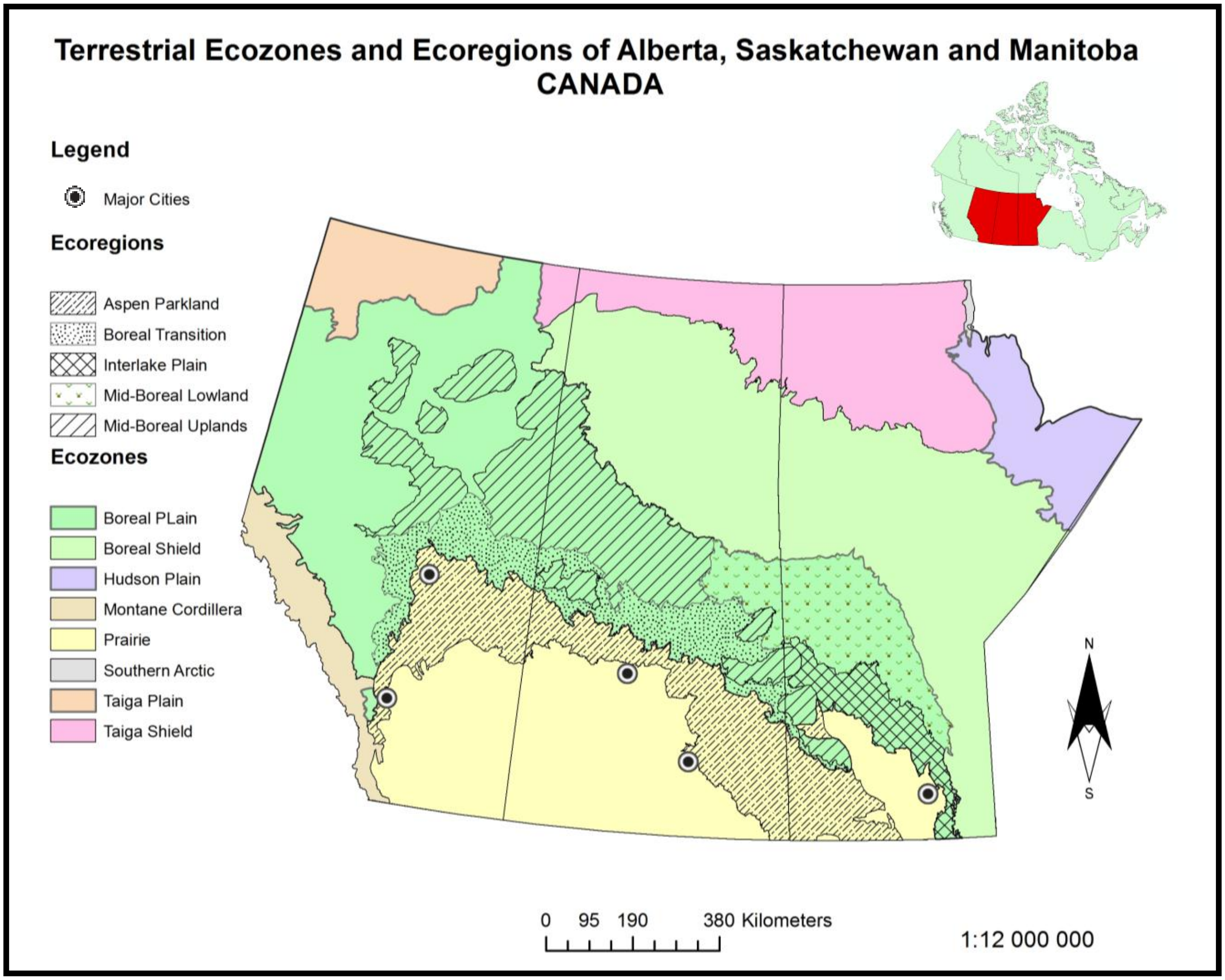

Figure 2: Ecozones and relevant ecoregions of the three Prairie Provinces of the Canadian Western Boreal forest

Box 1- Case Study: Elk Island National Park (EINP) - an example of an Island Forest

Significance: This area represents one of the largest blocks of aspen dominated lower boreal Mixedwood forest currently remaining in the Alberta landscape that is becoming extremely rare (Young et al. 2006).

Figure 3: Map delimiting the Elk Island National Park

Area: The EINP covers 194 km^2 on the Beaver Hills in east-central Alberta. It occurs on a hummocky moraine, formed during the retreat of the Late Wisconsinan glaciations 15,000 – 20,000 years ago (Campbell and Campbell 1997). The moraine is some 30-60 m above the surrounding plain.

Representative soils are podsols, ranging from Orthic Grey Wooded to Dark Grey Wooded soils that were developed on lacustrine, alluvial lacustrine, glacial till or alluvial aeolian materials (Soil Research Institute 1962).

Vegetation: The vegetation of EINP varies strongly with topography and latitude. The Beaver Hills have been classified as an outlier of the southern boreal forest (Rowe 1972); however, others have classified it as Aspen Parkland. The upland vegetation is closed-canopy poplar forest with a dense beaked hazel (*Corylus cornuta*) understory. Hilltops, south facing slopes, and recent burned areas often have meadows and ephemeral ponds (Campbell and Campbell 2000). In low wet areas, black spruce and tamarack (*Larix laricina*) are present, while north-facing slopes often have white spruce.

Land Cover Changes: This landscape has experienced a combination of land cover change processes from deforestation, fragmentation, and afforestation. The area of core forest patches greater than 300 ha has declined, with only 500 ha of core area remaining (Young et al. 2006), representing an 88% decrease since 1977. Afforestation in the Beaver Hills is in part a result of acreage and other landowners increasingly allowing their pastures to fill in with trees as well as the abandonment of marginal ranching or farming operations (Young et al. 2006).

Climate Change Implications for Western Canada's southern boreal forest

Increasing greenhouse gas emissions (GHG) such as CO_2, are now widely acknowledged as a major cause of recent increases in global mean temperature, about 0.5°C since 1970, and changes in the world's hydrological cycle (IPCC 2007). It is extremely likely (>95% probability) that warming over the past half century is due to human activities, as this trend in warming cannot be explained without including anthropogenic radiative forcing (IPCC 2007). Climate change has the potential to influence Canada's forest ecosystems through altered natural disturbance regimes, species distribution and forest productivity (Johnston et al. 2006). Climate change could have extensive consequences for ecosystems sensitive to changes in temperature and precipitation, such as grassland/woodland boundaries (Camill and Clark 2000). This may lead to a significant loss of natural forest with increased deforestation at the southern edge of the boreal forest and a correspondent large carbon pulse (Solomon and Kirilenko 1997). Climate change is already affecting Canada's forests; impacts include changes in forest fire regimes, large-scale insect outbreaks, drought in Central Canada, severe windstorms and shorter periods of frozen soil (Johnston et al. 2010b).

According to the IPCC, climate models project future climate changes by the year 2050 which would be unprecedented in the last 10,000 years. Predictions suggest that the rate of global warming will slowly accelerate, and projected global average surface warming at the end of the 21^{st} century is likely to be between 1.1 - 6.4°C depending on scenario (IPCC 2007). Canadian climate data collected over the past century has showed a warming of more than 1.3°C since 1948, a rate that is about twice the global average. Canada has also become wetter during the past half century as mean precipitation has increased by about 12%; however, portions of southern Canada (particularly the Prairies) have seen little change or even a decrease in precipitation, especially during the winter months (Johnston et al. 2010a).

Climate change will be significant in all of the prairie-parkland national parks (Elk Island, AB; Prince Albert, SK; Riding Mountain, MB) (Scott and Suffling 2000). These regions can expect increases in forest fire frequency and intensity, increase forest disease outbreaks and insect infestation, and loss of boreal forest to grasslands (de Groot et al. 2002). The Island Forests are at great risk to climate change. They are marginal or ecotone systems, borderline between grassland and forest ecosystems, and therefore sensitive to small changes in environmental conditions. As they are relatively small ecosystems, Island Forests may exhibit lower genetic diversity and greater vulnerability to catastrophic disturbance, such as wildfire, pathogen attack or severe drought (Henderson et al. 2002; Lemmen et al. 2008). Although vulnerable, these landscapes are also very valuable. They typically contain important species and ecosystem outliers at the very edge of their natural range, making them of conservation and scientific importance (Henderson et al. 2010). Trees are valuable in the prairie region; in Alberta these areas support a number of parks used for tourism and recreation and Island Forests are often of cultural and spiritual importance to Aboriginal people. Some island forest can also be used for timber harvest to support small communities, recreational needs, and small industry (e.g.: Fort à la Corne, Prince Albert, SK) (Henderson et al. 2002).

In addition to rising temperatures and changing precipitation regimes predicted under climate change scenarios, there are many other ongoing climatic changes that may impact tree growth and survival in the boreal fringe. Some positive predicted effects of increases in GHGs include a longer growing season as well as warmer soils, where more nutrients become available due to the increased rate of soil organic matter decomposition (Hogg 2002). Increased atmospheric CO_2 has the potential to enhance tree growth by increasing water use efficiency (WUE) and through CO_2 fertilization. WUE is the amount of carbon taken up through photosynthesis per unit of water loss. Under higher atmospheric CO_2 levels, less water is lost though transpiration, resulting in increased drought tolerance. However, increased drought frequency and intensity, inability of trees to adjust to changes in their environment, regeneration failure, increased forest fires, and potentially higher rates of insect and disease attacks may have drastic negative impacts on yields and timber supplies (Johnston and Williamson 2005; Spittlehouse and Stewart 2003) that far outweigh any beneficial effects of increased CO_2. Many studies have shown that the effect of long-term CO_2 enrichment is ambiguous regarding the relative success of increased growth and survivorship on plants. Different responses to elevated CO_2 have been observed among species within the same functional group and even among groups and individuals of the same species (Mohan et al. 2007). In addition, the initial increase in growth observed in carbon dioxide-enriched field studies tends to decline over time, a process known as acclimation (Long et al. 2004). Other impacts of a changing climate may include increasing ground-level ozone, rising UV-b levels, changing diurnal temperature patterns, and changes in timing and intensity of freeze-thaw events (Henderson et al. 2010). Increasing drought events, climate variability, flood events, thunderstorms and windstorms may also increase in frequency and will likely further increase stress on trees within this region (Henderson et al. 2010).

Climate Change Scenarios

A climate scenario is a plausible representation of future climate that has been constructed for explicit use in investigating the potential impacts of anthropogenic climate change (IPCC 2001a) . Studies of climate change impacts on ecosystems are typically based on climate scenarios generated by general circulation models (GCMs), operating at resolutions in the order of 200-300 km. GCMs are three-dimensional computer models which mathematically model the physical processes of the atmosphere, oceans, and cryosphere and land surfaces, and the relationships between these systems (Henderson et al. 2002). The GCMs included in this study are the most recent used by the IPCC and incorporated the latest Special Report on Emission Scenarios (SRES) emission scenarios. SRES emission scenarios were commissioned by the IPCC for its Third Assessment Report (IPCC 2001b) and are described in detail in Nakicenovic et al. (2000). They provide detailed scenarios of atmospheric composition (i.e. concentrations of greenhouse gases and aerosols) which are used within GCMs to determine the effect on the radiation balance of the Earth-atmosphere-ocean system (Henderson et al. 2002). The A2, A1B, and B1 SRES emission scenarios are referred to in this study and represent different potential world futures with respect to population and economic growth, energy use, technology development, etc. Each of these possible world futures implies a different trend in future emissions of green house gases and aerosols (Henderson et al. 2002). The three emission scenarios presented in this report were the only three available for study. The A2 scenario represents a divided world which is characterized by independently operating, self-reliant nations, a continuously increasing population, regionally oriented economic development with slow technological changes and improvements. The A1B emission scenario falls under the A1 category representing a more integrated world, rapid economic growth, a global population that reaches 9 billion in 2050 and then gradually declines, with a quick spread of new and efficient technologies. The A1B has a balanced emphasis on all energy sources. The B1 emission scenario represents an ecologically friendly, integrated world. This future has rapid economic growth but with changes towards a service and information economy. Similar to the A1 scenario, the population reaches a maximum at 2050 with 9 billion people and then declines. There is a reduction in material intensity and more clean and resource efficient technologies. There is an emphasis towards global solutions of economic, social and environmental stability. The growth rate of global emissions after 2000 has been approximately 3%, while the growth rates under the emission scenarios are between 1.4% and 3.4%. This has caused many to proclaim that these scenarios are too conservative (Garnaut et al. 2008) and will result in underestimations in coming decades, while, latter years may overestimate future emissions due to their failure to consider resource availability constraints (Höök et al. 2010). New scenarios or “Representative Concentration Pathways” are now being developed by the IPCC (Moss et al. 2010) and will be presented in the IPCC Fifth Assessment Report which is currently in progress.

Climate scenarios using five different GCMs and three different emission scenarios were constructed for the 2020s, 2050s, and 2080s according to standard IPCC guidelines (**Table 1**). For these five scenarios, yearly and monthly data was downloaded from the Canadian Climate Change Scenarios Network (CCCSN) website for the area encompassing the southern boreal fringe and forested regions (55.28° to 52.13° by -116.19° to -97.82°) (**Figure 3**). These five scenarios were chosen to represent a large range in temperature and precipitation variation under future conditions, it is important to try and capture the range of possible future conditions when doing scenario construction as there is large uncertainty associated with future predictions. Uncertainties will remain inherent in predicting future climate change, even though some uncertainties will likely be narrowed with time. Consequently, a range of climate scenarios should usually be considered in conducting an impact assessment (IPCC 2001a).

Table 1: SRES climate change models used in scenario construction and selected to represent a large range of climatic variation

GCM	AR4 SRES Emission Scenarios and range of variation			
	A2	B1	A1B	Range
GFDL CM2.1[1]	✓			Median
INGV-SXG [2]	✓			Warm, low precipitation
INMCM 3.0 [3]		✓		Medium temperature, high precipitation
MIROC 3.2 hires [4]			✓	Warm, medium precipitation
NCAR PCM		✓		Cool, medium precipitation

[1] Geophysical Fluid Dynamics Laboratory, National Oceanic and Atmospheric Administration (NOAA), United States

[2] Scoccimarro, E.; Istituto Nazionale di Geofisica e Vulcanologia, Sezione Bologna, Bologna, Italia

[3] Institute of Numerical Mathematics Ocean Model RAS, Moscow, Russian Federation

[4] Center for Climate System Research, University of Tokyo, National Institute for Environmental Studies, and Frontier Research Center for Global Change, Japan Agency for Marine-Earth Science and Technology (JAMESTEC)

[5] National Center for Atmospheric Research (NCAR), Parallel Climate Model (PCM) – Los Alamos National Laboratory (LANL), Naval Postgraduate School (NPG), US Army Corps of Engineers' Cold Regions Research and Engineering Lab (CRREL), United States

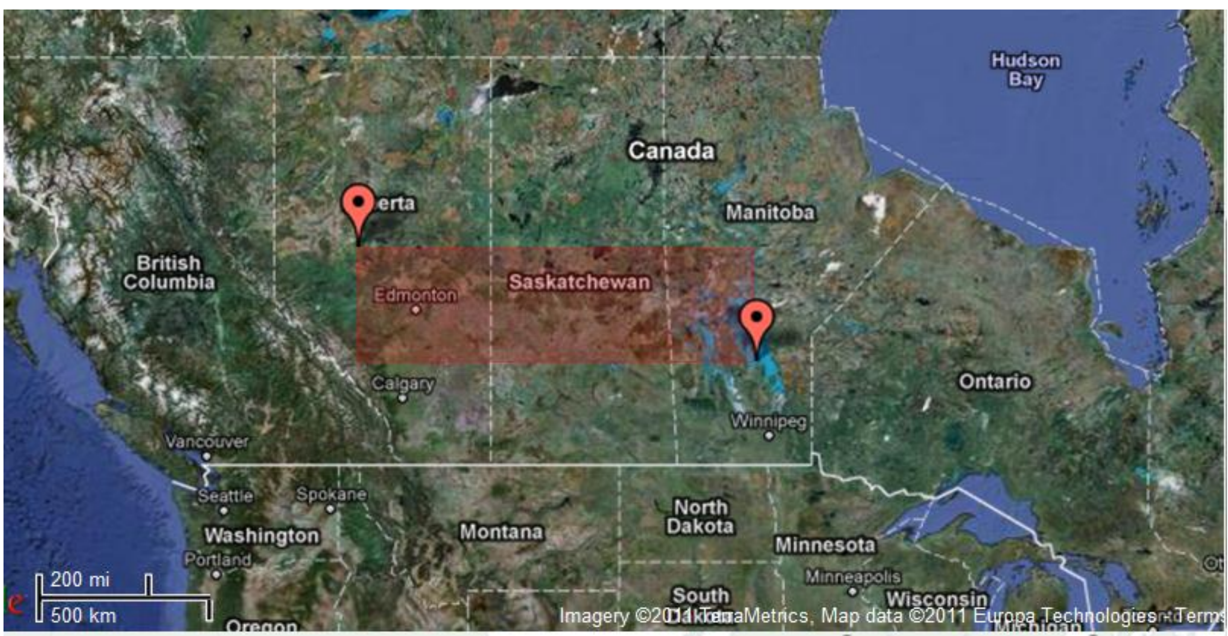

Figure 4: Map of Western Canada. Areas delineated in red were used in the scenario analysis to represent the Southern Boreal Fringe across the three Prairie Provinces

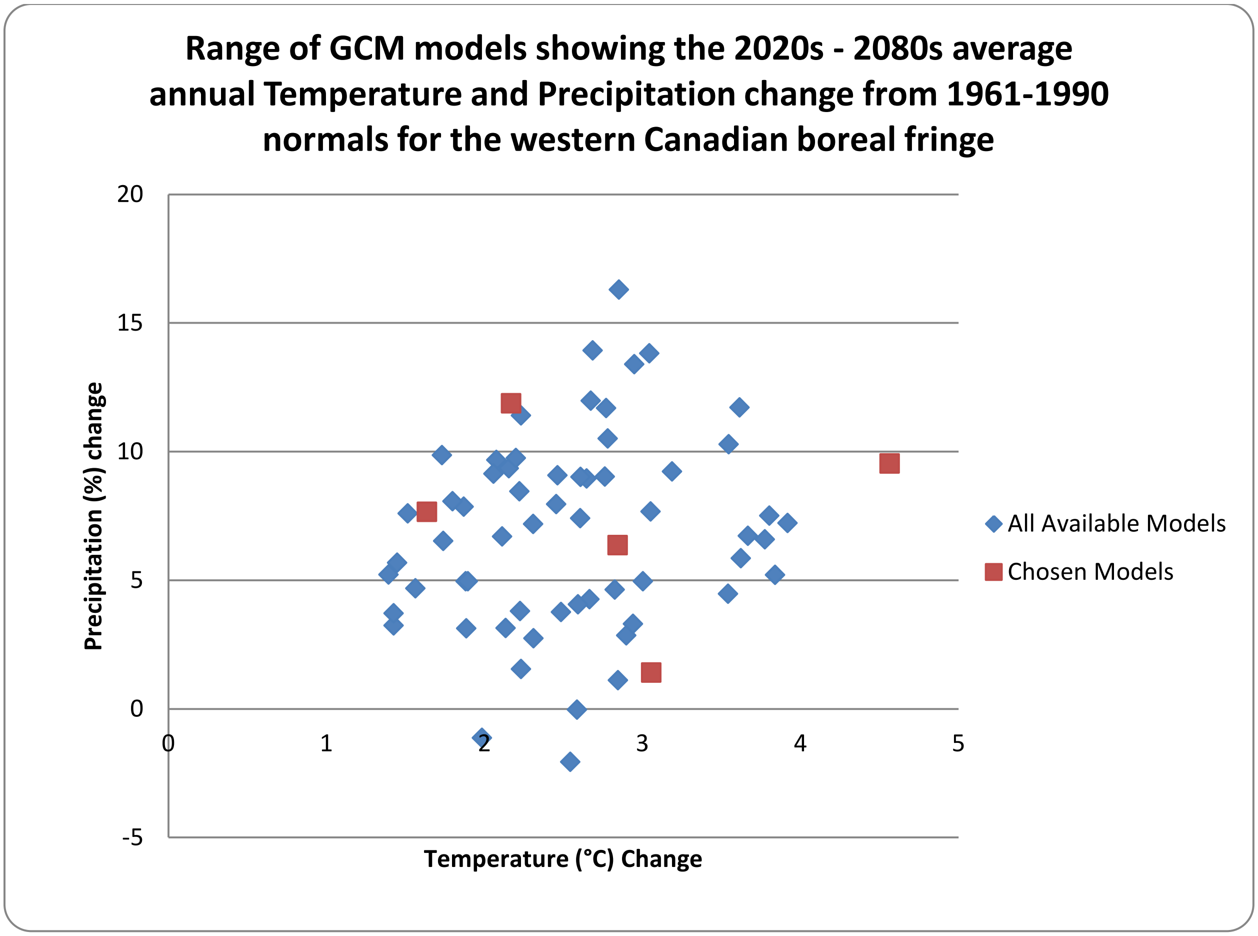

Figure 5: Range of GCM models chosen based on a large range of temperature and precipitation changes for the 2020-2080 periods as compared to the 1961-1990 normal.

The scatter plot method is usually the easiest way to choose a range of possible models in a scenario analysis. **Figure 4** shows a range of possible models that can be obtained from the CCCSN website, and the chosen models represent a range of temperature and precipitation change for future conditions averaged over the period of 2011 -2099. These models were further analyzed by creating a scatter plot for each individual time slice (2020, 2050, 2080) (**Figure 5**) and then into seasonal changes in temperature and precipitation changes (**Table 2**). This analysis was done to attempt to pick out any particular climatic trends for the boreal forest fringe. Trends show that models are more tightly clustered in the 2020s relative to the 2080s; therefore there is increasing range of potential temperature and precipitation in future conditions (or uncertainty) as we move further into future predictions. Precipitation ranges from negative values (below normal 1961-1990 period) in the 2020s and 2050s to up to a 13% positive change in precipitation. Precipitation largely decreases in the summer and autumn seasons with large increases during the winter, especially by 2080. Temperatures range from a 1-3°C change in the 2020s, to a 2-7°C increase by 2080s. Winter temperatures seem to show the most dramatic rise in temperature, especially by the 2080s. Other studies have shown that future climate scenarios predict warmer winters with greater precipitation, earlier springs, and summers with reduced soil moisture (Lemmen et al. 2008). The rise in winter temperatures also corresponds with an increase in growing season, by up to 50 days in the MIROC model (**Figure 6**).

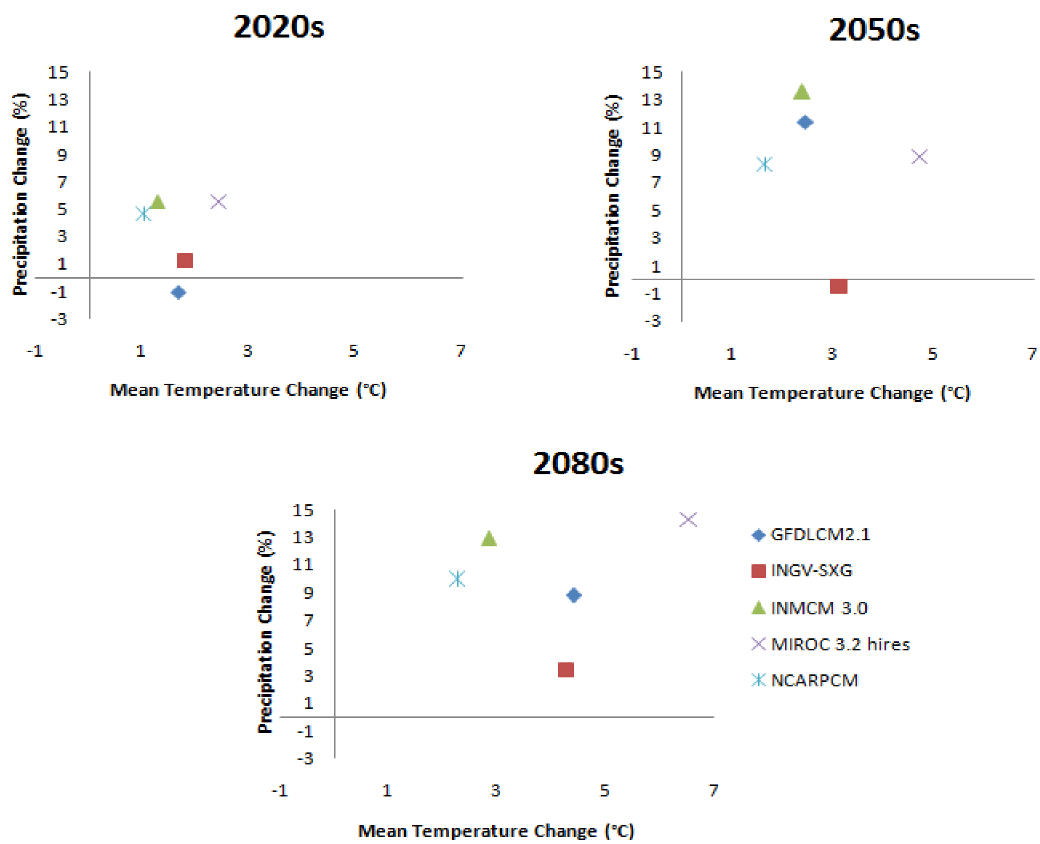

Figure 6: Scatter plots of annual mean temperature change (°C) versus precipitation change (%) over the western boreal forest fringe region for the 2020s, 2050s, and 2080s. All changes are calculated with respect to 1961-1990.

Table 2: Seasonal and annual changes in mean temperature (ΔT in °C) and precipitation (ΔP in %) over the western boreal forest fringe region for the GFDLCM2.1 A2 (Mid-range), INGV-SXG A2 (hot/dry), INMCM 3.0 B1 (warm/wet), MIROC 3.2hires A1B (hot/moist), and NCARPCM B1 (cool/moist) climate change scenarios. Numbers in red show an increase in temperature >3°C. Numbers in blue show a decrease in overall precipitation.

	Winter (DJF)		Spring (MAM)		Summer (JJA)		Autumn (SON)		Annual	
	ΔT	ΔP	ΔT	ΔP	ΔT	ΔP	ΔT	ΔP	ΔT	ΔP
2020s										
GFDLCM2.1 (A2)	2.92	1.81	0.77	5.61	1.45	-0.65	1.59	-11.64	1.68	-1.06
INGV-SXG (A2)	2.23	3.92	1.92	-3.74	1.35	2.58	1.72	3.78	1.80	1.29
INMCM 3.0 (B1)	1.52	3.83	1.38	**19.09**	0.98	**10.31**	1.26	3.10	1.28	9.10
MIROC3.2hires (A1B)	2.86	2.15	2.90	**11.74**	2.02	3.82	1.99	4.44	2.44	5.51
NCARPCM (B1)	1.89	-0.27	0.94	7.65	0.71	3.50	0.56	7.39	1.03	4.65
2050s										
GFDLCM2.1 (A2)	3.78	9.02	1.82	**20.12**	2.04	**11.42**	2.12	2.71	2.44	11.35
INGV-SXG (A2)	4.16	4.46	2.47	1.06	2.72	-1.93	3.11	-4.68	3.11	-0.51
INMCM 3.0 (B1)	3.45	**14.71**	2.03	**24.35**	1.58	**14.21**	2.44	5.78	2.38	13.61
MIROC3.2hires (A1B)	5.75	**15.31**	5.49	**24.54**	3.72	-8.65	3.98	**11.31**	4.73	8.85
NCARPCM (B1)	2.60	8.20	1.33	**11.60**	1.05	5.88	1.55	**10.82**	1.63	8.35
2080s										
GFDLCM2.1 (A2)	6.05	**17.08**	3.29	**37.86**	4.59	-8.51	3.73	-0.97	4.41	8.81
INGV-SXG (A2)	4.97	**11.86**	4.07	1.09	3.80	-1.81	4.19	6.52	4.26	3.43
INMCM 3.0 (B1)	3.85	**11.68**	2.66	**13.06**	1.93	**27.23**	2.99	**10.73**	2.86	12.9
MIROC3.2hires (A1B)	7.81	**33.06**	7.32	**31.73**	5.42	-6.90	5.56	**11.00**	6.53	14.25
NCARPCM (B1)	3.87	**15.94**	1.79	**12.55**	1.43	8.67	1.97	5.59	2.26	9.99

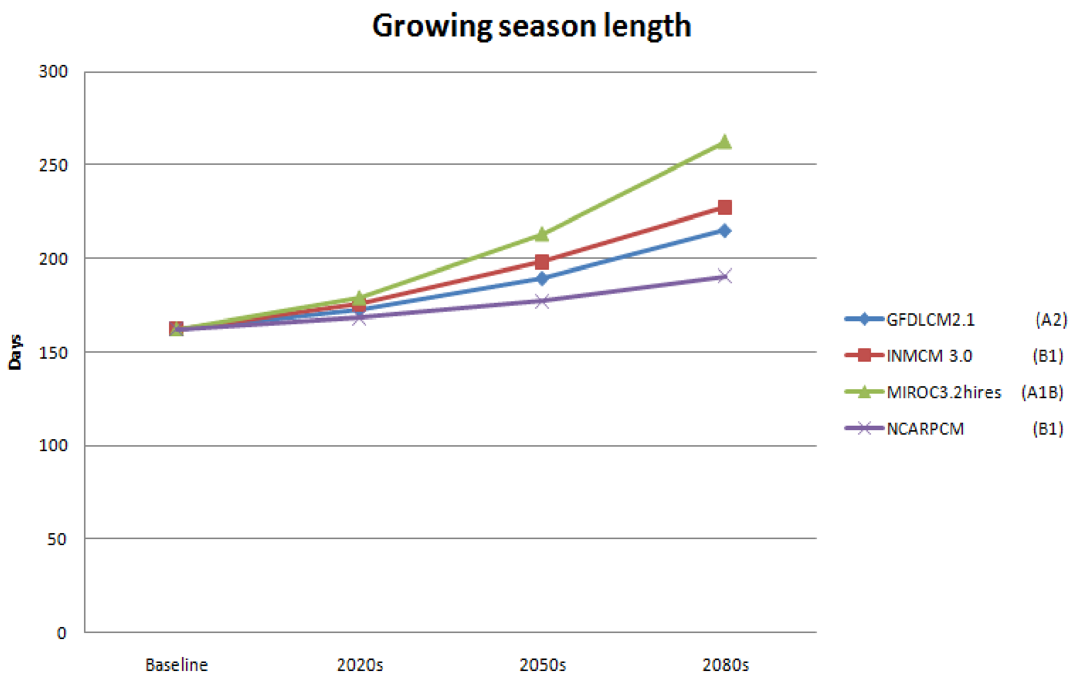

Figure 7: Number of Days in the growing season over the western boreal forest fringe in Canada as predicted by 4 GCMs. Baseline conditions represent the period from 1961-1990.

Vulnerability Assessment

The purpose of a vulnerability assessment is to evaluate how susceptible an organization (or ecosystem) is to climate change, and identify areas on which to focus adaptation efforts (Sustainable Resource Development 2010). Many social, biological, and geophysical systems are at risk from climate change impacts, vulnerabilities, and associated risks that may be considered "key" because of their magnitude, persistence, and other characteristics (IPCC 2007). The IPCC defines vulnerability as "the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes". When adaptation measures are intensified, the vulnerability is reduced (Santoso 2007). Turner et al. (2003) describe vulnerability as a function of three overlapping characteristics: exposure, sensitivity and adaptive capacity. This concept was later expressed mathematically by Metzger et al. (2006), where vulnerability (V) is a function of exposure (E), sensitivity (S) and adaptive capacity (AC):

$$V = f\ (\mathrm{E, S, AC})$$

Exposure (E) is the nature and degree to which ecosystems are exposed to an environmental change (e.g.: higher temperature). Sensitivity (S) is the degree to which the natural environment is affected by change (e.g.: drier forests lead to forest fires), while adaptive capacity (AC) is the ability of a human system (or ecosystem) to adapt to the impacts of climate change (e.g.: planting drought resistant trees). In human settings, adaptive capacity is determined by access to technology, available resources, and social and human capital. Vulnerability can be assessed in the context of either current or future climate scenarios and adaptation measures can then be proposed that may decrease vulnerability by reducing potential negative impacts and improving adaptive capacity (Johnston 2010; Johnston et al. 2010a)

The SRD's Climate Change Adaptation Framework was used to identify key vulnerabilities for the forests of Alberta. A vulnerability assessment considers the sensitivity of ecosystem services and socio-economic sectors to changes in climate variables such as temperature and precipitation, and the existing adaptive capacity of an organization to respond to this sensitivity, in order to arrive at an assessment of vulnerability (Sustainable Resource Development 2010). Specific systems prone to stress, like the Island Forests, may be seriously impacted in the future from climate change and should be considered highly sensitive. Couple this with portions of the forest that lack capabilities to adapt to a warmer climate (e.g. due to fragmentation, genetic variance, tolerance limits) and reduced human capacity (restricted policies, lack of resources) and forest vulnerability may become significant. The overall goal of this work is to provide information that can be used to support sustainable forest management and the maintenance of ecosystem services under future climatic changes by identifying the greatest sources of risk. The following sections review some of the main vulnerabilities foreseen within the Southern Boreal Fringe of western Canada and provide a review of current scientific information on these ecosystem services.

Ecosystem Services:

Water Regulation

Forests play both a direct and indirect role in water regulation by protecting water quality and quantity to meet human needs by reducing soil erosion, mitigating salinity, altering yield and timing of water by reducing storm flow peaks and absorbing large amounts of soil moisture (Hamilton 2008). However, many of these forest qualities will not be considered in the context of the southern Boreal Forest Fringe as they are not applicable to this area.

The primary concern involving water in the southern Boreal Forest Fringe is the occurrence of drought. Drought events are predicted to increase in frequency, duration, and severity over the course of the next century. In their vulnerability assessment, SRD predicted that Alberta's forests would be **highly vulnerable** (sensitivity = high, adaptive capacity = low to medium) to drought caused by climate change events (**Table 3**). Drought inevitably results in a multitude of consequential effects on forest ecosystems, including increased forest fire, increased sensitivity to insects and disease, increased tree mortality and regeneration failure, which will be addressed in more detail in later sections. Drought is expected to be especially important in the western southern Boreal Fringe as some areas are already moisture limited.

Table 3: Degree of sensitivity, adaptive capacity and vulnerability of Alberta's forests to impacts of climate change on water regulation (H=High; M= Medium; L= Low)

Ecosystem services	Key projected Climate Change impacts	Vulnerability Assessment		
		Degree of Sensitivity (H/M/L)	Degree of Adaptive Capacity (H/M/L)	Vulnerability (H/M/L)
Water regulation	Drought	H	L-M	H

Drought is a normal part of climate variation. A drought occurs when there is an extended period of months or years when a region experiences a deficiency it its water supply, usually caused by a lack of precipitation. It is a recurring extreme climate event, and considered a temporary dry period, in contrast to the permanent aridity in arid areas (Dai 2011). Drought can have significant impacts on ecosystems as virtually every plant process depends on water to operate. Although droughts can persist for years, a short intense drought can also cause significant damage to economies (e.g.: Australia) (The Environmental eZine 2007). One of the most sensitive and immediate plant responses to water stress at the cellular level is a reduction in the growth of processes including cell division and enlargement (Kramer 1983). Photosynthesis is not as sensitive, declining slowly until water stress becomes moderate to severe (Kramer 1983; Mattson and Haack 1987). If water stress continues for an extended period of time, mortality of the plant eventually occurs.

Exposure

GCM predictions are in general agreement that the climate of the southern boreal forest fringe will likely become warmer and drier in the future, especially in the summertime owing to greater water loss by evapotranspiration (Cubasch et al. 2001; Gregory et al. 1997). Projections vary from slight (-1 to -2% change in soil moisture) (Seneviratne et al. 2002) to severe (-15% change in soil moisture) (Wetherald and Manabe 1999) increases in aridity for the mid to high latitudes. Hogg and Hurdle (1995) predicted future climate of the western Canadian interior would include a 4.2°C increase in mean daily maximum temperature, a 4.9°C increase in mean daily minimum temperature, and an 11% increase in precipitation under a doubling of atmospheric CO_2. Under this scenario climate conditions would actually become drier as the increase in precipitation would not be enough to compensate for the increase in temperature and evapotranspiration (Hogg and Hurdle 1995; Schindler and Donahue 2006). Regional climate models indicate that the predicted warming could increase evaporation by up to 55% in certain areas of Alberta, Saskatchewan, and Manitoba (Schindler and Donahue 2006). Therefore, whether the precipitation increases or decreases, the southern boreal fringe is likely to experience much drier conditions in the future due to higher temperatures. There is increasing evidence that droughts in the prairie provinces will be similar to the western Canadian drought of 2001-2003 (Hogg et al. 2006) but will occur at a higher frequency and severity in the future. Johnston et al. (2006) identified major drought events that could span multiple years to decades as a critical climate change issue for forest fringes in the Prairies.

Sensitivity

Trees under drought stress have a number of physiological adaptations that allow them to deal with lack of moisture for a limited time. Adaptations to drought are evident from the changes in species composition and drought hardiness that occur along moisture gradients (Franklin and Dyrness 1988). McDowell et al. (2008) postulated three mutually non-exclusive mechanisms by which drought can lead to broad scale forest mortality. The first mechanism, hydraulic failure, is caused by cavitation of the water columns within the xylem during extreme drought and heat stress, preventing the flow of water. This occurs when the tree continues to transpire under conditions of limited moisture. Anisohydric species are those that have xylem more resistant to negative water potential resulting from cavitation, and have some ability to tolerate drought. With the second mechanism, carbon starvation, stomata close completely to reduce water lost by transpiration. However, this may cause eventual carbon starvation as stomatal closure shuts down photosynthesis while respiration costs continue depleting carbon stores (Allen et al. 2010). Species able to tolerate some degree of stomatal closure are termed isohydric species. Carbon starvation may result in mortality, but it also may reduce the tree's ability to defend against attack by biotic agents such as insects and fungi. The third mechanism, biotic agent demographics, occurs over extended warm periods during which higher temperatures can drive increased abundance of pests, allowing them to overwhelm their already stressed tree hosts. In general, anisohydric species are more common in drought-prone habitats as compared to isohydric species (McDowell et al. 2008).

Trees are adapted to the local average water availability; therefore, extreme drought events can cause reduced plant growth, C allocation, primary productivity, survival and regeneration (Chmura et al. 2011; Kolstrom et al. 2011; McDowell et al. 2008). Drought stress will also predispose forests to damage by insects, diseases and wildfires, potentially leading to shifts in species distributions and large-scale changes in forest community composition and structure (Chmura et al. 2011). Insects and disease, especially those whose life cycles are favored by warmer temperatures (Volney and Fleming 2000), are predicted in increase in abundance and may cause forest dieback. Drought and insect defoliation events both operate at large spatial scales, and their combined impacts can lead to severe consequences on forest health and regeneration. From 1951-2000, drought and insect attack lead to a regionally averaged growth reduction of up to 50% across a large portion of the western Canadian Interior (Hogg et al. 2005). A severe drought in western Canada from 2001-2003 led to a pronounced decrease in growth and dieback of this region's aspen forests. During the drought period, there was a major increase in wood-boring insects, and modest increases of fungal pathogens (Hogg et al. 2006). Prolonged droughts and hot spells will further aggravate the risks of forest fires. Drought conditions have a strong link with fire since the risk of fire increases with increasing drought duration and intensities, and depends on annual and seasonal moisture and temperature changes (Cerezke 2009). As vegetation dries it becomes more combustible and thus provides fuel for fires (Kolstrom et al. 2011). Models that estimate the future climate under warmer and drier conditions suggest an increase in fire across the Canadian forests on the whole, with the area burned possibly doubling over the next century (Balshi et al. 2009a; Flannigan et al. 2005; Natural Resources Canada 2009). Under future conditions, fire or pathogen attack could permanently remove forest cover in the boreal fringe and island forests if conditions become too dry for trees to regenerate (Henderson et al. 2010). The single most important factor limiting successful establishment and performance of forest regeneration in the Island Forests is moisture availability. Hogg and Wein (2005) identified that forests are very sensitive to drought during the regeneration phase and drier conditions due to climatic change could exacerbate this vulnerability and restrict or prevent regeneration. Drought conditions have and will prevent establishment of species on a site and cause mortality of established seedlings (Nitschke and Innes 2007).

Western forests in Canada are viewed as more vulnerable to climate change impacts than eastern forests because of higher variability of climate and the increased drought risks (Cerezke 2009; Sauchyn and Kulshreshtha 2008). 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 (Cerezke 2009). Trembling aspen is one of the most economically important deciduous tree species in the North American boreal forest and is the dominant tree in the aspen parkland zone along the northern edge of the Canadian prairies (Hogg et al. 2005), where it forms stunted patches of forest interspersed with cropland and grassland. Trembling aspen is expected to be especially vulnerable to the impacts of a warmer and drier future climate (Hogg and Hurdle 1995) and has already deteriorated because of drought, repeated defoliation by forest tent caterpillar (*Malacosoma disstria*), or both (Hogg and Schwartz 1999). Michaelian et al. (2010)'s report on the massive aspen mortality following severe drought along the southern edge of the Canadian boreal forest. They recorded 45 Mt of dead broadleaf trees during 2005-2006, covering an area of 11.5 Mha, four years following an exceptional drought. In the Island Forests, recent work has shown that moisture deficits have the potential to limit the success of current reforestation practices such as natural (drag scarification in jack pine and suckering following harvest of aspen) and artificial (direct seeding and planting) renewal treatments (Bendzsak 2006). These 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 species of the Boreal and Parkland Zones (Cerezke 2009).

Drought is regarded as a major limiting factor for determining the range limits of tree species (Sykes and Prentice 1995). It plays a direct role in shaping species distributions (Aber et al. 2001) altering composition, structure, and biogeography of forest landscapes (Allen et al. 2010). Trees grow relatively slowly, but can die quickly in response to drought. Therefore, mortality of adult trees can result in ecosystem changes far more quickly than a gradual transition driven by tree regeneration and growth (Shafer et al. 2001). The southern boreal fringe is highly sensitive to changes in moisture, especially drought because moisture is already limited in this region. Drought effects are most likely to occur first at semiarid ecotones such as the transition zones from prairie to boreal forest and drought induced mortality is likely to be patchy in these fragmented regions (Allen and Breshears 1998; Michaelian et al. 2010). Therefore, western Canada's southern boreal fringe is predicted to be highly vulnerable to the impact of climate change induced drought stress in the coming years. As climate becomes warmer and drier in the future, the southern margin of the boreal forest will becomes increasing vulnerable and may eventually lose forest cover. Recent research suggests that there will be increasing tree mortality from the interactions of drought, insects and fire at the southern margin of the boreal forest in the Prairie

Provinces. Information regarding the interacting effects of drought with insects and fire will be addressed in greater detail in later sections.

Habitats and Landscapes

Forested landscapes provide habitat for wildlife and supply many essential goods and services to humans, including game animals, fuel wood, timber, flood control, and recreation. Climate change impacts are expected to cause shifts in forested ecosystem types (e.g.: conversion of conifer to aspen dominated forest), habitat loss, and increased fragmentation which may result in changes or a loss of ecosystem services. SRD's gauged that Alberta's forests would be **highly vulnerable** (Sensitivity = Medium; Adaptive Capacity = Medium) to these impacts. Many scientific studies also predict that considerable changes will occur on the southern edge of the boreal forest, involving a total loss of forested habitat and a shift into a grassland ecosystem. SRD rated this impact as **highly vulnerable** (Sensitivity = Medium; Adaptive Capacity = Low to Medium) to Alberta's forests (**Table 4**).

Table 4: Degree of sensitivity, adaptive capacity and vulnerability of Alberta's forests to impacts of climate change on habitats and forest landscapes (H=High; M= Medium; L= Low)

Ecosystem service	Key projected Climate Change impacts	Vulnerability Assessment		
		Degree of Sensitivity (H/M/L)	Degree of Adaptive Capacity (H/M/L)	Vulnerability (H/M/L)
Habitats and Landscape	Shifts in forest ecosystem types	H	M	H
	Habitat loss and increased fragmentation	M	M	M
	Loss of forest ecosystems/habitat (forest to grassland climate shift)	M	L-M	H

Exposure

As GHG emissions continue to rise, conservative climate change scenarios predict increases in global mean temperature of about 2-4°C globally by 2080, with significant drying in some regions (Christensen et al. 2007; Seager et al. 2007). The rate of warming is expected to be much larger (3-8°C), in the northern continental areas that include much of the world's boreal forest (Hogg 2002). Many aspects of climate change predictions remain shrouded in uncertainties, but the climate record already shows that large areas of the boreal forest have experienced a warming of about 1.5°C over the past century (Hogg 2002). Temperature trends for 1900-1998 show an annual mean daily maximum temperature increase for southern Alberta (Zhang et al. 2000) with the greatest warming occurring in the spring months. By 2050 the mean temperature across the prairies is expected to increase by 2-4°C, compared with the 1961-1990 reference period, and even greater increases are possible under extreme climate scenarios (Sauchyn and Kulshreshtha 2008). There is less certainty with respect to precipitation changes, but most models indicate an increase of up to 15% increase can be expected and most of these gains will occur in the winter and spring (Sauchyn and Kulshreshtha 2008). Actual precipitation trends observed over the last 50 years have actually been the opposite, with an approximately 15% decrease in precipitation observed over the prairies and central mixedwoods of Alberta (Mbogga et al. 2009). Even if precipitation does increase slightly, most regions will become drier during the growing season because of the effects of increased heating on evapotranspiration. These conditions will become the catalyst for shifts in species composition at the landscape level along the southern boreal forest. Species will likely redistribute or die out, resulting in new plant communities with no current analogue. Wildlife species associated with various forest types will shift as their habitat changes, or in some cases disappear (Johnston et al. 2006).

Sensitivity

The Canadian boreal forest is one of the ecosystems most at risk under global climate change, as high latitude biomes in particular, will be subject to more extreme warming relative to mid and low latitudes (Scholze et al. 2006). Changes in climate of the magnitude projected for the 21st century have already caused substantial vegetation change in the past (Mbogga et al. 2009; McKenney et al. 2009; Parmesan 2006b; Williams et al. 2004), so it is prudent to expect that the current dynamics of northern forests may change within the timeframe of concern to resource managers (Chapin III et al. 2004). Under a changing climate, trees will either need to **adapt** to new climates, **migrate** with shifting environmental zones, or become **extirpated** from the landscape (Aitken et al. 2008; Melillo et al. 1993).

The strongest patterns of local adaptation in temperate and boreal forest trees reflect the critical synchronization of the annual growth and dormancy cycle of populations with their local seasonal temperature regimes. If trees have a shorter than optimal period of active growth relative to their local climate and available growing season, they will not have competitive growth rates. If growth is initiated too early in spring or continues too late in the summer or early fall, cold injury may result. In most temperate and boreal species, the initiation of growth occurs in spring (Aitken et al. 2008). Climate change will not alter photoperiodic cues for growth cessation and bud set, but may delay the fulfillment of chilling requirements in winter or accelerate the satisfaction of heat sum requirements, and may also change the degree of synchrony for reproductive bud development among populations affecting the potential for long distance gene flow via pollen (Aitken et al. 2008). **Adaptation** may be impossible in areas where many forest species currently thrive, as climate may change too quickly to provide the species' necessary survival requirements (Papadopol 2000; Thompson et al. 2009). Many conifer species are widely distributed; however, populations within those species are finely adapted to their native climatic environments within a relatively narrow climate range (O'Neill and Yanchuk 2005). Under circumstances where climate becomes significantly different from that in which the species evolved, maladaptation occurs. Maladaptation includes a direct climate component, e.g. increasing temperatures, and an indirect component, e.g. changes in soil moisture caused by changes in precipitation and evapotranspiration (Johnston et al. 2010a). These climatic-related effects also render trees more susceptible to additional stressors, like insects, disease and fire (Frey et al. 2004; Kliejunas et al. 2009; Volney and Hirsh 2005). Maladaptation is likely to occur to many species currently present in the southern boreal fringe if temperatures continue to rise and drought events increase in frequency. Maladapted vegetation will likely die off over time and cause a shift in successional trajectories within this region. This can alter the current resilience of the system during the establishment phase and new communities may form consisting of plants better adapted to the warmer climate. The transition to new vegetation types is likely to be slow as long as mature trees are present but may proceed quickly if the mature trees are killed by a disturbance, leaving a site that is struggling to regenerate and vulnerable to a change in species mix (Hogg and Wein 2005). One can expect these disturbances to be discontinuous in time and space as they will reflect the distribution of natural disturbances more than changes in the mean climate (Flannigan et al. 2001; Hogg et al. 2002a). Fire is one agent that has the ability to rapidly change the landscape, and is expected to increase over the next century due to warmer and drier temperatures. Many boreal species are adapted to fire, however proper regeneration of pine and spruce requires the presence of cone bearing trees. If fire frequency increases and the fire return interval become shorter than the time for seedlings to reach sexual maturity, many pine and spruce trees could be extirpated from the landscape. Therefore, we can expect an increase in the dominance of aspen in high fire zones, even if there is sufficient soil moisture for conifer seedling survival (Hogg and Bernier 2005). This will lead an increase in relative abundance of fire adapted vegetation in the island forests and boreal fringe as conifers eventually become replaced with aspen (Campbell and Campbell 2000; Johnston et al. 2006). This in turn could translate into decreased fire activity over time even in a warmer and drier climate as aspen forests are less prone to fire (Krawchuck et al. 2006). Lags and thresholds could lead to sudden large responses to future climate change that are not readily apparent from current vegetation (Camill and Clark 2000). Shifts in the distribution of vegetation communities can be expected to lag behind changes in the bioclimatic envelope. This is primarily because mature individuals of most tree species have substantial tolerance to climatic fluctuations and can persist for extended periods outside of their usual climatic envelope (Hogg 1994; Schneider et al. 2009). In addition, the ability of species to migrate in response to changing conditions may be limited by the human-dominated landscape. Initial responses to greenhouse warming could be modest if local factors buffer vegetation against regional climate change. This buffer may create a lag in ecosystem response and sharpen transitions between vegetation types (Camill and Clark 2000).

The forests affected earliest and most drastically are located at the southern edge of the biome (Davis and Zabinski 1992). Overstory trees may persist for four or five decades, but seedlings would not. The latter are more sensitive to climate change and may disappear within a few decades, setting the stage for local extinctions of tree populations and associated understory plants. This will result in a loss of current habitat over time with increasing fragmentation occurring as forested areas begin to exhibit the effects of a changing climate. The fewer number of trees in the environment represented either by the number of occupied habitats or the abundance within habitats, the fewer seeds will be produced. Fewer suitable habitats results in a lower probability that seeds will land in a suitable site and successfully recruit (Carter and Prince 1988b). Shifting of geographical ranges of plant communities due to warming cannot occur at the rate at which warming will likely proceed (Weber and Stocks 1998).

Species residing in areas like the island forest that exist on the fringe of the southern boreal forest may lack the genetic diversity or required gene flow to adjust to different climates, and are isolated on a restricted landscape with a lack of migration pathways. Species within the island forests will be limited geographically by the low frequency of suitable habitats. Carter and Prince (1988a; 1988b) predicted that although species may be common locally within a suitable habitat, the probability of habitat colonization is very low when patches of suitable habitat are rare. Near species distribution limits, population extinction rates equal new site colonization rates because suitable habitat is rare. As the probability of colonization approaches that of local extinction, a species ceases to expand its range (1988a; Carter and Prince 1988b).

Large shifts are expected in the distribution of Canada's forest biomes over the next 50 years due to climate change (Henderson et al. 2010). The capacity of plant species to fill redefined ranges will be strongly influenced by their **migration** rates (Higgins et al. 2003). As paleobiology records demonstrate, most conifer species have tolerated large and repeated changes in climate through widespread migration (Jackson and Overpeck 2000; Webb and Bartlein 1992). However, the magnitude of species' redistributions and the ensuing evolutionary lag that accompanied those events may well have resulted in prolonged periods of ecological disturbance that today would have significant negative social, environmental, and economic ramifications (O'Neill et al. 2008). Paleo-ecological data provides only limited insight for contemporary climate change, because change is now more rapid than in the past (Huntley 1991), will result in higher global temperatures than previously experienced over the last several million years (Cowley 1990), and is occurring in a different biological setting (McMahon et al. 2009). Migratory responses necessary to track climates far exceed maximum post-glacial rates (Aitken et al. 2008). Today, estimated average rates of tree migration range from 1-10km/century (fragmented landscapes), (Schwartz et al. 2001) to 50 km/century (fully forested landscapes, (McKenney et al. 2007; Schwartz et al. 2001). In contrast, GCMs, species distribution models, and global vegetation models predict an average northward shift of 700 km in suitable climate over the next century (Barnes 2009; McKenney et al. 2009). Consequently, the respective migration rate required by trees to keep pace with climatic change would be 14 times the current estimated rate of migration. The extent to which populations will adapt depends upon phenotypic variation, strength of selection, reproductive capacity, interspecific competition, and biotic interactions (Aitken et al. 2008). Under modern settings, the migration capacity of tree species in the Island Forests will also be limited by restricted dispersal due to their isolated setting. Over the next several decades, the climate in the southern boreal forest is predicted to shift northward (Chapin III et al. 2004; Hogg and Hurdle 1995; McKenney et al. 2007) causing species' ranges to become redefined. Schneider et al. (2009) used a combination of a bioclimatic envelope model and a transitional disturbance model to predict how the landscapes in Alberta would be affected by climate change. They found that much of the southern boreal forest would be converted to parkland, and other studies have shown that the current parkland zone could become converted to grasslands overtime (Hogg and Hurdle 1995). In addition to slow dispersal rates, trees may have to contend with inhospitable environments when attempting to migrate (Johnston et al. 2010a). Barriers exist across the landscape in the form of agriculture, urban environments, and lack of suitable soil conditions in the north of current distributions (Higgins et al. 2003; McKenney et al. 2009).

Extirpation of trees from the landscape and replacement by new biomes will likely occur over an extended period as mature trees are present and disturbances will be needed to remove them from the landscape. Recently, in the southern boreal forest there have been noted cases of increased tree mortality and die-off triggered by drought and high temperatures that may be indicative of some forest response to climate change (Hogg et al. 2002a). The southern boreal forest will be at significant risk from climate change as it is a marginal system, bordering the grassland, and sensitive to small changes in environmental conditions. The IPCC Working Group II (1996) noted that a warming of average annual temperature of as little as 1°C (in the absence of increased moisture) could be enough to shift the forest northward, while the southern limit of the boreal forest converts to grassland or other non-boreal species (Wheaton 1997). Temperatures predicted for this area will be much higher than 1°C, increasing the risk of these landscapes as their adaptive climate moves northward out of their current range and they are unable to keep pace. These changes in the climatic environment will be large stressors on an already weak system, and with increases in disturbances (fire, drought, insects) the future of the forests in the region is questionable. As moisture limitations increase over time, the inability to regenerate, drought stress, pests, and fire will slowly fragment the forest edge, causing forest diebacks and disappearing trees. Grasses will likely expand into this region, gradually replacing the trees. The impact of these changes will likely result in changes to technology, markets and recreational values in this area (Johnston and Williamson 2007).

Therefore, habitats and landscapes in the southern boreal fringe of the Prairie Provinces could slowly become degraded and fragmented over time as climate change continues. This may initially lead to changes in dominance of tree species (e.g. conifer to aspen) or changes in species mix. As climatic stressors exceed species tolerances, trees will suffer higher mortality, reduced regeneration, and other disturbances such as fire may permanently remove them from the landscape. Grasses will begin to encroach on these areas over time as trees become extirpated from the landscape. This shows that these regions are highly vulnerable to change if future conditions occur as predicted by GCMs.

Pest Regulation

Forest pests, such as insects and diseases, are integral components of forest dynamics, in which they fulfill important roles. These roles include providing food for other insects, spiders, birds and small mammals, removing weakened trees to make room for healthy plants, pollinating flowers, breaking down plant material to improve nutrient cycling, and aiding succession (Alberta Sustainable Resource Development 2009a). They are normally present at low densities, causing little damage, and negligible impact on tree growth and vigor (Allard et al. 2003). Occasionally, these pest populations can grow rapidly in response to favorable environmental conditions and cause extreme damage. Such sporadic outbreaks can have catastrophic impacts on forests and trees, in some cases leading to the complete destruction of large areas of forest, reduction of vital forest ecosystem functions, and considerable economic losses (Allard et al. 2003). These large scale pest outbreaks are also a natural part of the boreal system to which it is adapted. The concern over pest outbreaks occur when the frequency, extent, and intensity of large population eruptions goes beyond the natural range of variability for which species are adapted and impact the system’s ability to recover. These effects can have many adverse effects on tree growth and survival, yield and quality of wood and non-wood products, wildlife habitat, recreation, aesthetics, and cultural value. Forest insects and pathogens are the most ubiquitous and important agents of disturbance in North American forests, affecting an area almost 50 times larger than fire and with an economic impact nearly five times as great (Logan et al. 2003). Due to the pervasive and potentially damaging effects of forest pests under future climatic conditions, SRD determined that the forests of Alberta would be **highly vulnerable** to increasing invasive species and biotic forest health damaging agents (Sensitivity = High; Adaptive Capacity = Low to Medium) (**Table 3**). This would be especially true for the southern boreal forest fringe within the Prairie Provinces.

Table 5: Degree of sensitivity, adaptive capacity and vulnerability of Alberta's forests to impacts of climate change on Pest Regulation (H=High; M= Medium; L= Low)

Ecosystem service	Key projected Climate Change impacts	Vulnerability Assessment		
		Degree of Sensitivity (H/M/L)	Degree of Adaptive Capacity (H/M/L)	Vulnerability (H/M/L)
Pest Regulation	Increasing invasive species and biotic forest health damaging agents. Impact created by altered species diversity.	H	L - M	H

Exposure

There are significant adverse impacts and indications that outbreaks of forest insect pests and diseases are on the increase across the globe (Allard et al. 2003) as warming temperatures have direct effects on insect population dynamics. Insect physiology is highly sensitive to temperature, with metabolic rate tending to about double with an increase of 10°C (Gillooly et al. 2001). Therefore, climatic warming tends to accelerate insect consumption, reproduction, development, and movements, which can influence population dynamics via affects on fecundity, survival, generation time, and dispersal (Bale et al. 2002; Bergeron and Leduc 1998; Mattson and Haack 1987). The timing of life history stages of many insect species has already been demonstrably advanced by warming temperatures (Logan et al. 2003) by trapping efforts in the UK which have already provided evidence that the timing of critical life history events – the most easily observed response of ectothermic organisms to a warming climate - is occurring earlier among insects than previously recorded (Harrington et al. 2001). There are also increasing examples of insect distributions extending northward (Parmesan 2006a) with reports of growing damage from some forest pests at the poleward and alpine limits of their historical occurrences (Jepsen et al. 2008; Lima et al. 2008). In addition to increasing insect metabolism during the growing season, climatic warming also reduces the risk to insect populations suffering winter mortality from extreme cold (Bale et al. 2002). Already, extreme minimum temperatures have increased by 3.3°C in the southeastern US from 1960-2004. Over that same time period, outbreaks of southern pine beetle have extended northward by ~200 km, matching the predictions of physiologically based models of cold tolerance for this species (Bale et al. 2002; Tran et al.

2007). A similar example was recently experienced in Canada with the mountain pine beetle (*Dendroctonus ponderosae*), outbreak in British Columbia (Regniere and Bentz 2007), which has now spread to areas of Alberta. In fact, Cullingham et al. (2011) show for the first time a successful mountain pine beetle attack in natural jack pine stands at the leading edge of the epidemic. Once unsuitable, this habitat is now a new environment for this species to exploit, and represents a potential risk which could be exacerbated by further climate change with significant consequences for the boreal forest ecosystem (Cullingham et al. 2011).

The range of many pathogens is limited by climatic requirements for overwintering or oversummering of the pathogen or vector (Garrett et al. 2006). Similar to insects, higher winter temperatures (-6° to -10°C) have been shown to increase survivorship of overwintering rust fungi (*Puccinia* graminias) and caused increased disease on fescue (*Festuca)* and ryegrass (*Lolium*) plants (Pfender and Vollmer 1999). Research into the effects of climate change on plant diseases is limited; however Coakley et al. (1999) stated that climate change could alter stages and rates of development of pathogens, modify host resistance, result in changes in the physiology of host-pathogen interactions and cause a shift of the geographic distribution of both the host and pathogen resulting in new disease complexes. Temperature is the dominant climate factor in terms of direct effects on diseases through effects on their overwintering capabilities, although precipitation effects have not been studied sufficiently to draw general conclusions (Garrett et al. 2006).

Sensitivity

Climate influences the survival and spread of insects and pathogens directly, as well as the susceptibility of their forest ecosystems (Dale et al. 2001). Plants growing in marginal climates, like the Island Forests, could experience chronic stress that would predispose them to insect and disease outbreaks. As already noted, drought and higher temperatures, are expected to cause greater stress on these landscapes. Drought stress promotes outbreaks of plant fungi and insects by providing a more favorable thermal environment for growth, survival, and reproduction (Mattson and Haack 1987). Drought stressed plants are also more attractive for insects due to leaf yellowing, greater infrared reflectance, and decreased defenses. Warming and other changes could also make trees more vulnerable to new pathogens that are currently not important due to unfavorable climate (Coakley et al. 1999). However, because climate change can both directly and indirectly affect herbivores and pathogens through various processes, the ultimate effects on patterns of disturbance include increases in some areas and decreases in others (Dale et al. 2001). Insect infestations and disease promote fire by increasing fuel loads, and fires can promote future infestations by compromising tree defenses (Dale et al. 2001).

Insects

Every aspect of an insect's life cycle is dependent upon temperature because they are cold blooded. Therefore, these organisms quickly react to a changing climate by shifting their geographical distribution and population behavior to take advantage of new climatically benign environments (Carroll et al. 2003). Insect pests possess a great capacity to alter habitats and modify ecological processes in forests, often leading to extensive ecological and economic damage (Dukes et al. 2009; Fleming and Candau 1998; Liebhold et al. 1995). The most important ensuing effects from insect defoliation are mortality, growth loss, rotation delays, and increased susceptibility to secondary insects and disease (Kulman 1971). Important pests such as spruce budworm, jack pine budworm and forest tent caterpillar are expected to increase due to the direct effects of temperatures on reproduction, and the increased susceptibility of host trees due to other stresses (Hogg and Bernier 2005; Hogg et al. 2002a; Johnston et al. 2006). In aspen stands, small defoliation effects by insects cause reduced growth and twig dieback but no impact on stem mortality. If severe defoliation occurs for three consecutive years it can lead to an increase in fungal pathogens and insect borers, with a significant increase in stem mortality 6-10 years after the infestation (Hogg et al. 2002a). Tree-ring records taken by (Hogg et al. 2002b) in Grande Prairie, AB area showed two periods of strongly reduced growth of aspen, both of which coincided with major defoliation events in the study area. The first was between 1961- 1963, when mean stem area increment decreased by 75%, and the second occurred between 1977-1980, when a decrease of 64% was recorded. According to Sterner and Davidson (1982), moderate to severe insect defoliation of aspen covered over a total aggregate area of 20 x 10^6 ha in the Canadian Prairie Provinces during 1977-1981. Future impacts of climate change are of a concern because in a warmer and drier future climate insect effects have the potential to be more severe. One of the major concerns for the western Canadian Interior is presently found at the northern edge of the prairies, where aspen stands are stunted and prone to severe dieback during periods of drought (Hogg and Hurdle 1995) making them especially vulnerable to insects and disease. After age and drought, pests have a major influence on aspen survivability with forest tent caterpillar and *Armillaria* root disease accounting for 15.9% and 14.6% of the total variation in the percentage of healthy tress and standing dead (Brant et al. 2003). As discussed previously, an important consequence of climate change is higher frequency, intensity and severity of droughts. In addition to causing mortality through carbon starvation and cavitation of water columns within the xylem, climatic water stress can have profound effects on tree susceptibility to attack by pests (Bentz et al. 2010). Drought can affect growth, defense, tissue repair, and the production of constitutive or inducible chemical defenses, and thereby limiting the ability of the tree to responds to invasions.

The following section will consider the individual effects of three important pests on North American trees and how they may be affected by climate change. These following insects cause vast outbreaks which often end in extensive replacement of forest stands and could have a significant role in modifying the southern boreal forest fringe.

Forest Tent Caterpillar

Forest tent caterpillar (FTC), is the most important pest of trembling aspen in the Prairie Provinces, and causes reductions in growth and tree mortality when outbreaks occur (Brant et al. 2003; Hildahl and Reeks 1960). Outbreaks can often last 3-4 years, and the repeated defoliation over that time period can significantly affect tree productivity and mortality (Horsley et al. 2002). Studies in Alberta and Saskatchewan have showed that the caterpillars significantly affect growth of trembling aspen and is strongly associated with crown dieback, often evident several years following the outbreak (Hogg and Schwartz 1999). Increasing defoliation events can be associated with an increase in proportion of weakened, or declining and dead aspen trees (Brant et al. 2003). This caterpillar favors warm, dry summer conditions and therefore, its impacts on aspen, in combination with drought, will probably increase under climate change (Hogg et al. 2002a; Ives 1981). Currently, outbreaks are limited to some extent by low winter temperatures (-33°C) that kill eggs. As winter temperatures increase across the southern boreal forest fringe, the threshold for egg survival will be surpassed and outbreaks may become more extensive (Virtanen and Neuvonen 1999).

Warmer winter temperatures projected by climate change might suggest an increase in overwinter survival of FTC eggs (Dukes et al. 2009). However, studies have shown that cold tolerance in the FTC eggs varies seasonally in response to temperature. As result, a sequence of warm days can decrease egg glycerol content, thereby decreasing cold tolerance of the eggs (Hanec 1966), and causing them to be more vulnerable to cold events during the winter months. This effect was observed in an Alberta FTC outbreak following a winter that experienced sudden transition between extreme warm and extreme cold which caused sudden egg mortality (Cooke and Roland 2003). Therefore, if winters become warmer as predicted by climate change scenarios, then a small bout of extreme cold could easily prevent or shorten periods of FTC outbreaks by decreasing the winter survivability of their eggs, thus reducing future effects of FTC on aspen stands (Dukes et al. 2009). Therefore, if there are increased variance in climatic extremes in winter temperatures, FTC larvae could be more at risk (Dukes et al. 2009). Alternatively, other climate models also predict fewer freezing events in late winter and early spring, which would decrease FTC egg mortality (Dukes et al. 2009; Hayhoe et al. 2006).

Synchrony between larval emergence and budbreak of plants is important for survival and growth of FTC and many other early season lepidopteran defoliators, this cycle may become disrupted under climate change. For early season feeders, optimal growth occurs when caterpillars have access to young foliage. Therefore it is important for larvae to hatch at the proper time. If they emerge too early they can starve, and if they hatch late they can suffer reduced growth rates, longer larval stages, and lower papal masses, indicating reduced female fecundity (Jones and Despland 2006). Climate warming is already having discernable effects on the phenology of plants and their first leaf dates often occur earlier in the year (Schwartz et al. 2006). If FTC and tree hosts respond differently to thermal cues, climate change could result in changes in FTC outbreaks (Dukes et al. 2009). Therefore, the impacts of future outbreaks of FTC will greatly depend on the climate which can either aid or hinder future outbreaks on this pest and subsequent effects on aspen forests.

Bark Beetle (*Mountain Pine Beetle*)

Bark beetles have evolved with coniferous forests ecosystems of western North America and are highly sensitive to thermal conditions for survival and growth. Outbreaks of these beetles have been correlated with shifts in temperature (Powell and Logan 2005) and precipitation (Berg et al. 2006), while water and heat stress can decrease host tree vigor and its resistant to beetle invasion. The response of bark beetles to climate change can be characterized by a high degree of complexity and uncertainty as beetle populations are directly influenced by temperature and indirectly influenced through other climatic effects on trees (Bentz et al. 2010). Early studies showed that temperature directly controlled MPB mortality, and cold exposure was considered the key factor controlling bark beetle population dynamics. In south eastern BC, the distribution of MPB was thought to be controlled by the position of the -40°C isotherm, which limited its eastward spread across Canada (Safranyik et al. 1974). These results have been increasingly questioned in its applicability to MPB in north BC and Alberta environments. MPB overwintering mortality appears to follow different rules in forests where MPB is a novel disturbance (Bleiker 2001). Results of future temperature driven climate models developed for estimating the spread of spruce beetle and mountain pine beetle warn us to expect positive changes in bark beetle populations throughout the coming century.

The mountain pine beetle, offers an intriguing and relevant example of the interaction between climate, host trees and reproduction. This species will successfully attack most western pines, but lodgepole pine is its primary host (Carroll et al. 2003). In 2001, Logan and Powell (2001) wrote that "it is anticipated that under global warming, former climatically hostile environments will become climatically benign, allowing mountain pine beetle to significantly expand its range". This prediction was proven correct; in 2008 there was a large outbreak of MPB in B.C., Canada. Over 14.5 million hectares were infested initially, and it is expected to kill close to 80% of B.C.'s mature pine forests. This outbreak was cause in part by increasing temperatures which created warm winters allowing this beetle to spread. This outbreak has seen the expansion of MPB beyond its historical range into lodgepole pine stands in northern BC and west-central Alberta. Currently, the leading edge of this outbreak has moved into the lodgepole pine – jack pine hybrid zone and into pure jack pine stands as well (Cullingham et al. 2011). Due to an unusual weather event, MPB was brought to west-central Alberta for the first time in 2006. Strong winds carried beetles approximately 400 km from central BC to the Grande Prairie region, infesting pine forests in the area (Alberta Sustainable Resource Development 2009b). As temperatures rise throughout the century, the area suitable for MPB is predicted to grow (Bentz et al. 2010) and susceptibility of jack pine to MPB is a major concern (Cullingham et al. 2011). An increase in low temperature survival is predicted for spatially isolated areas of Canada, including west-central Alberta, where MPB has recently been found attacking lodgepole/jack pine hybrids (Nealis and Peter 2009), and Cullingham et al. (2011) has shown the first successful MPB attack in a natural jack pine stand. Bark beetle outbreaks in the retreating and expanding margins of tree distributions, will play an important role in colonizing and killing stressed individuals as they attempt to adapted to a changing environment (Bentz et al. 2010).

Spruce Budworm

The spruce budworm, *Choristoneura fumiferana,* is the most important defoliator pest of spruce-fir forests in North America, and is widespread across prairie boreal forests, attacking white spruce, tamarack and balsam fir. The life history of the spruce budworm is similar to other conifer-feeding species. Eggs are laid in the summer, hatch and feed on fungi without causing damage to needles (Retnakaran et al. 1999). They overwinter on branches and emerge in spring to feed on needles and developing buds of conifer trees (Volney and Fleming 2000). Spring emergence of spruce budworm larvae is the most critical step in determining whether populations will thrive, and must be timed correctly with host phenology. Therefore, successful establishment of this species requires proper synchrony between insects and host development (Volney and Fleming 2000). This species also has the ability to rapidly evolve with its host species if environmental conditions change due to large genetic variability, lack of strong reproductive barriers and excellent dispersal abilities. Therefore, under a warming climate, the entire range of white spruce across the boreal forest should be considered vulnerable to spruce budworm outbreaks (Volney and Fleming 2000). In the prairie and the aspen parkland ecoregions, white spruce are often confined to north facing slopes of ravines or moist regions in the Island Forests. Budworm outbreak in these areas persist for several years and become terminated only by late frosts that damage the entire crop of current year's shoots thus starving developing larvae (Cerezke and Volney 1995). Persistent budworm outbreaks disrupt forest stand development, killing trees and opening stands to permit surviving tree to prosper. Forests damaged by spruce budworm may also be more prone to fire and can burn more intensely due to increased fuel loads (Stocks 1987). The majority of results assessing spruce budworm's response to climate change indicate intensification in all aspects of outbreak behavior (Logan et al. 2003).

Disease

Climate change has the ability to alter the incidence and severity of tree diseases such as, stem diseases, heart wood rots, stem decay, shoot blights and cankers, foliar and root diseases, mistletoes, viruses and virus-like disorders, vascular wilts, and seed and seedling diseases (Johnston et al. 2006). Losses from forest diseases in Canada are estimated to be 36 million cubic meters of timber annually, which translates to one-third of the total annual harvest. Changes in climate may result in pathogen expansions into the host habitat range, or conversely, the host could be released from disease by changes in environmental conditions that make the climate unfavorable to the pathogen (Harvell et al. 2002). Fungal responses to climate are complex and interactions with tree host susceptibility, insect vectors, and important belowground interactions between fungi and tree roots are not well studied (Allen et al. 2010). Each fungus possesses different thermal ranges for optimal growth (Rice et al. 2008), and seasonal temperature dictates which fungal species is transmitted by dispersing insects (Six and Bentz 2007). It continues to be difficult to predict how plant pathogens will respond to climate change as they can survive and infect their hosts under a wide range of temperatures (Agrios 2005), but conditions needed to produce epidemic outbreaks can be constrained within a few degrees Celsius. The following diagram (**Figure 7**) was adapted from Dukes et al. (2009), and describes the probable direct and indirect effects of climate change on forest pathogens:

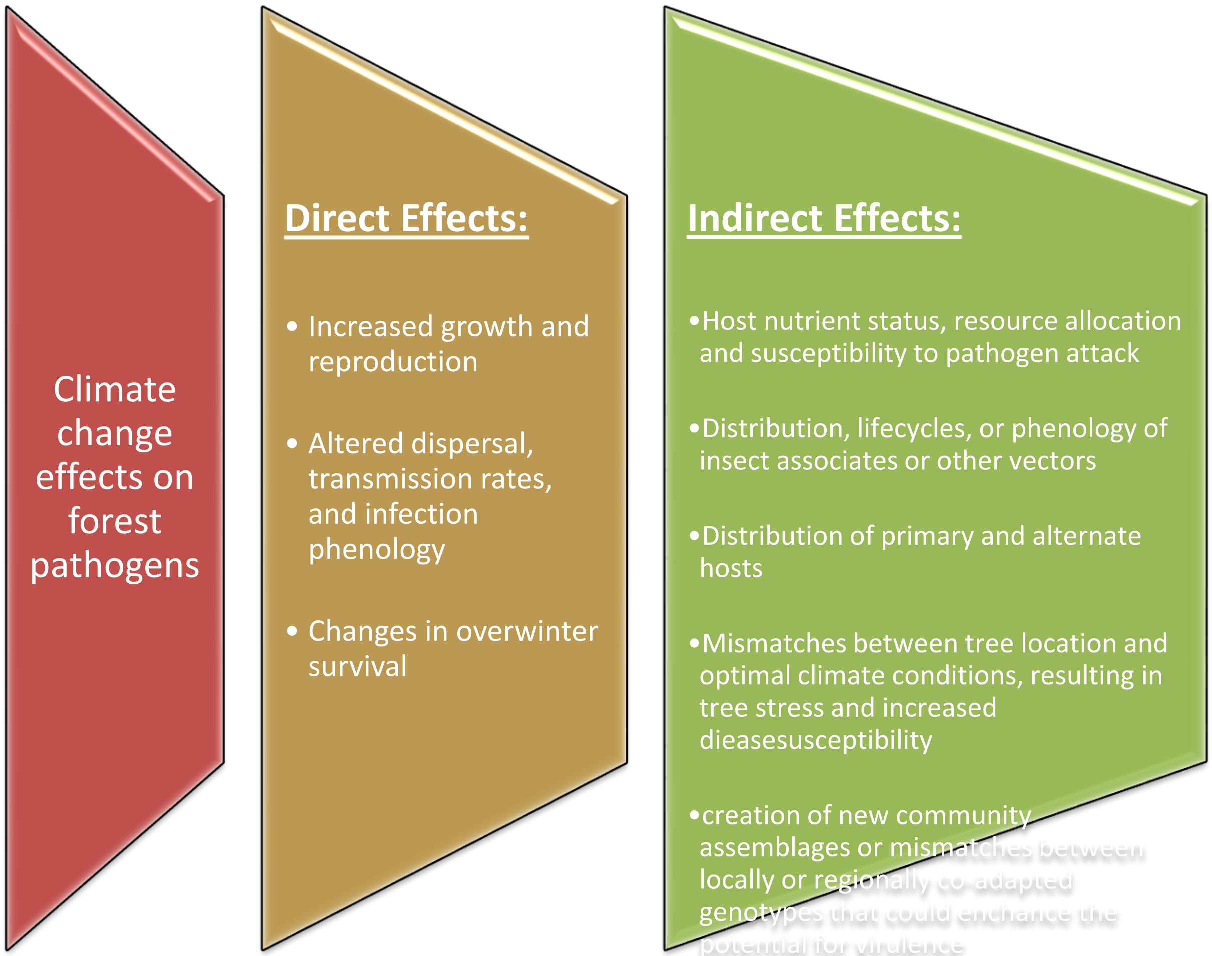

Figure 8: Direct and indirect effects of climate change on forest pathogens

Lodgepole Pine Dwarf Mistletoe

An example of one of the most damaging pathogens of jack pine in western Canada is lodgepole pine dwarf mistletoe (DMT) (*Arceuthobium americanum*). Dwarf mistletoe has two major hosts, lodgepole pine, and jack pine. In the United states, DMT is a major pathogen and is estimated to have infected over 11.7 million hectares of forest (Dale et al. 2001). In Canada, the presence of DMT severely infects jack pine throughout the western region (Brandt et al. 2004). This disease has devastating effects on growth and vigor, and ultimately causes tree mortality. Mistletoe infestations also reduce wood quality, impair and reduce seed productivity to the extent that heavily infected branches do not produce regenerative structures (McIntosh 2004). This disease is extremely invasive and persistent, often re-infecting young stands from sources within and adjacent to the stand following disturbance (Bendzsak 2006). The presence of DMT also increases fire hazard by creating additional standing dead and downed wood. Species that are insusceptible or have reduced susceptibility to this disease would be worth investigating as reforestation alternatives (Bendzsak 2006). Optimal temperature conditions for survival of dwarf mistletoe is from 12°C to 16°C, while winter temperatures below -39°C result in significant mortality (Brandt et al. 2004; Smith and Wass 1979). Currently more northerly areas are free of DMT; the northern limit of DMT is 59°N, where it occurs on jack pine in Alberta (Brandt et al. 2004). If winter temperatures increase under climate change, DMT may have increased survivability and infection rates because fewer winters will have temperatures severe enough to eliminate the year's cohort of mistletoe infections. The southern limit of this species is in California; therefore, temperatures in southern boreal Canadian forests are unlikely to become too warm for the survival of this species as a result of climate change (Johnston et al. 2008). In addition, it is likely to expand its range northward as winters subside (Johnston et al. 2008).

Genetic Resources

Two main vulnerabilities of forest resources to climate change in the boreal forest of western Canada are the loss of species and the loss of within species forest genetic resources. Both of these vulnerabilities were rated as a medium vulnerability (Sensitivity = Medium; Adaptive capacity = Low to Medium) under predicted climate change (**Table 6**). Since climatic factors have a distinct influence on the spatial genetic differentiation of forest trees, it is essential to look at which climatic factors affect trees in order to match populations to planting sites for adapting to the expected future climate changes.

Table 6: Degree of sensitivity, adaptive capacity and vulnerability of western Canada's boreal forests to impacts of climate change on Genetic Resources (H=High; M= Medium; L= Low)

Ecosystem service	Key projected Climate Change impacts	Vulnerability Assessment		
		Degree of Sensitivity (H/M/L)	Degree of Adaptive Capacity (H/M/L)	Vulnerability (H/M/L)
Genetic Resources	Loss of species	M	L - M	M
	Loss of within-species forest genetic resources	M	L - M	M

Genetics and Trees

The genetic structure of plant populations is inextricably linked with variation in the physical environment (e.g., Linehart and Grant 1996), because the environment provides both the habitat and a selection pressure to sort populations according to their reproductive fitness (e.g., Futuyma, 1979). Because of their sessile and perennial nature, forest trees provide an excellent material for studying the relationship between plants genetics and the environment. Morgenstern (1996) discussed general principles of forest tree genecology and provided examples of geographic variation trends in temperate and boreal forests. A literature review by Rweyongeza and Yang (2005) showed that, the relationship between genetic differentiation and climate is greater in the northern latitudes (temperate and boreal) than in the tropics. Generally, the sharp changes in temperature along latitudes and altitudes, large seasonal variation in temperature and day length, and post-glacial recolonization history account for patterns of genetic variation in forest trees observed in this region (e.g., Morgenstern 1996).

Extensive studies of conifer provenances (populations) have shown that the pattern of genetic variation is similar among species. This chapter provides only a brief summary of the observed patterns in the context of this report. A comprehensive review of variation by species and regions is found in Rweyongeza and Yang (2005); a similarity in genetic variation patterns between forest trees and other plants in well covered by Linhart and Grant (1996). In trees, genetic variation among populations is predominantly clinal. (1) Growth potential declines from lower to higher latitudes and from lower to higher elevations. (2) Populations at higher latitudes and elevations open and set buds earlier than those at lower latitudes (also see Howe at al. 2003). (3) In more climatically harsh environments such as higher latitudes and to some extent higher elevations, survival and growth potential are maximized by local populations (e.g., Rweyongeza 2011; Rweyongeza et al. 2007a; Rweyongeza et al. 2010; Rweyongeza et al. 2007b). (4) A trade-off exists between growth potential and parameters of survival such as cold hardness (e.g., Loehle 1998), which explains the conservative growth modes of marginal tree populations.

Provenance studies in white ash (*Flaxinus Americana* L) by Roberds et al. (1990), aspen (*Populus tremuloides* Michx) by Gray et al. (2011) and Gray and Hamann (2011) and western alder (*Alnus rubra* Bong.) by Hamann et al. (2000) show that deciduous species exhibit a variation pattern similar to conifers. Although conifers, seed propagated deciduous and clonally propagated deciduous species exhibits different modes of pollen and seed dispersal, and regeneration, they respond to similar environmental selection pressure. For clonal species such as aspen where the same genotype persists for millennia, this selection may have occurred during post-glacial colonization of their present natural ranges.

Key to all species is the association between genetic differentiation and climate (Linhart and Grant 1996; Davis et al. 2005). Studies show that climate is a major natural selection pressure that explains genetic variation in quantitative traits such as growth and thus, productivity. Provenance studies of Canadian species have contributed immensely in our understanding of this relationship and its consequences in light of climate change. Interested leaders should consult Rehfeldt et al. (1999, 2001) and Wang et al. (2006) for lodgepole pine (*Pinus contorta* Dougl.), Rweyongeza et al. (2007a, 2007b, 2010) and Andalo et al. (2005) for white spruce (*Picea glauca* [Moench] Voss), Thomson and Parker (2008) and Matyas and Yeatman (1992) for jack pine (*Pinus banksina* Lamb) and Thomson et al. (2009) for black spruce (*Picea mariana* [Mill) BSP) to name just a few. Similar studies exist outside Canada (e.g., Schmidtling 1994; Mátyás 1994). It suffice to say that, in addition to revealing the relationship between tree population genetics and climate, these studies show that climate change can have a serious negative impact on forest productivity. This is particularly true in the boreal region of western Canada where significant moisture deficit exist.

The ability of the species to adapt (survive, grow and reproduce) to its environment depends on its ability to continuously adjust its gene pool to remain in equilibrium with the challenges of the current environment. When the change in the environment is gradual and spread over a longer period, organisms such as forest trees can evolve by natural selection (differential survival and reproduction) to produce populations and genotypes that are suitable for the environment (e.g., Futuyma 1976). The ability of the species to evolve genetically and adapt to a changing environment is tied to the existence of genetic variation among and within populations (e.g., Falconer and Mackay 1996). Therefore, the essential requirement for enabling a species (plant or animal) to sustain itself in a changing environment is to conserve its genetic variability. Changes in climate are expected to occur faster (e.g., Barrow and Yu 2005; Mbogga et al. 2010), even though the extent of change differs among modeling scenarios. Regardless of climate change scenarios, the changes are faster than the rate of evolution in forest trees due to longer generation intervals. With generation intervals spanning decades, forest trees can neither evolve nor migrate as fast as the rate of projected changes in climate. Therefore, maintaining forests in climatically stressed environments such as the southern fringe of the species in the Canadian Prairies has two components namely, (1) conserving the unique gene pools characteristic of that area, and (2) maintaining forest productivity where commercial forestry currently exist.

Timber Resources

Timber is wood in any of its stages from felling through readiness for use as structural material for construction, or wood pulp for paper (Wikipedia contributors 2011b). Globally, forests cover around 30% of the Earth's land surface and each year billions of cubic meters of wood are harvested for industrial roundwood and fuel wood usage by humans (Food and Agriculture Organization 2005). The effects of climate change impacts on forests will undoubtedly have serious impacts on both natural and modified forests. As discussed earlier, vegetation is expected to shift with warming trends, expanding into current tundra area as far as soil conditions might allow. However, forests at the trailing edge will likely be reduced and this could lead to a massive loss in natural forests with increased deforestation at the southern boundary. All the impacts of climate change on the forest as described in previous sections will affect both biophysical and economic aspects of the timber supply in Canada. There will be effects on the quality and quantity of timber and the quantity and location of salvage (Geilsenan 2007). The magnitude and type of effect in any given region will be dependent on the climate change in that region (Lempriere et al. 2008). Some growth and yield models demonstrate that climate change can increase global timber production through a poleward shift of the most important forestry species (Kirilenko and Sedjo 2007). Climate change also has the ability to accelerate growth due to warmer climate, longer growing seasons, and elevated atmospheric CO_2, and thus increase overall long-term timber supplies (Lempriere et al. 2008). On the other hand, many other impacts of climate change have the ability to decrease forest production, such as increased fires, drought, insects, pathogens, and other extreme events (Johnston and Williamson 2005; Ohlson et al. 2005; Spittlehouse and Stewart 2003). Climate change may also have a dampening effect on prices of forest products in the global market as higher growth rates lead to increased wood supply, especially in developing countries (Sohngen and Sedjo 2005). These impacts of climate change will ultimately be the drivers that influence changes in forest structure and productivity at local levels and lead to changes in how forests are managed (Johnston and Williamson 2005). The southern boreal fringe is especially important as most timber of commercial value is found within this region, the relatively warm climate and deep soils support a diverse and productive mix of pure conifer forests and mixed woods consisting of white spruce, jack pine, or black spruce mixed with trembling aspen, balsam poplar or white birch (PARC). Warmer temperatures, drought events, increase fire activity, and pest occurrence will likely result in a loss of forest productivity for the southern boreal forest fringe along the Prairie Provinces. A decrease in forest productivity will cause a loss in timber supply and land rent value. SRD predicted that the boreal forest, and in turn the timber supply, would be highly vulnerability of to increasing forest fires, increase in forest health damaging agents, regeneration failure, loss of timber and commercial forest land base. The degree of sensitivity in this system would range from high to medium and the adaptive capacity would range from medium to low (**Table 7**).

Table 7: Degree of sensitivity, adaptive capacity and vulnerability of Alberta's forests to impacts of climate change on Genetic Resources (H=High; M= Medium; L= Low)

Ecosystem service	Key projected Climate Change impacts	Vulnerability Assessment		
		Degree of Sensitivity (H/M/L)	Degree of Adaptive Capacity (H/M/L)	Vulnerability (H/M/L)
Timber	Increasing frequency and extent of **forest fires**	H	L	H
	Increase in severity and extent of many forest health damaging agents	H	L-M	H
	Regeneration failure and reduced tree growth/survival due to drought and severe weather events	M-H	L-M	H
	Loss of timber due to increased fire and forest health damaging agents	M-H	L	H
	Loss of revenue from shift and net depletion of **commercial forest land base**	M-H	L-M	H

Exposure

Under climate change scenarios, fire frequency is predicted to increase over the next century. Fire activity is strongly influence by four factors – weather, fuels, ignition agents and humans (Johnson 1992). In Canada, fire seasonal severity rating may increase by 46% (Flannigan and Van Wagner 1991), and fire season length may increase by approximately 30 days (Wotton and Flannigan 1993). Bergeron and Flannigan (1995) expect that under global warming, the average fire weather index (FWI) would increase over Western Canada but decrease in the east (Li et al. 2000). Regeneration of forest species, especially conifers, is expected to be significantly reduced in the southern boreal forest if the CMI decreases to less than -15 (Hogg and Schwartz 1997). For example, a future warming of 2°C would represent summer temperatures empirically associated with extreme levels of stress and an empirically predicted level of zero growth for white spruce (Chapin III et al. 2004). Climate change is expected to reduce forest productivity because of increased fire frequency, extent and increased pest damage (O'Neill et al. 2008) which will ultimately lead to a loss of timber in the southern boreal forest. Carbon dioxide (CO_2) concentrations have risen from a preindustrial value of 270 to 390 umol mol $^{-1}$, and are predicted to at least double in the next century (Millard et al. 2007). These rising concentrations are predicted to increase tree growth if other resources in the environment are not limiting (e.g. moisture and nutrients).

Sensitivity

The effects of climate change on Canada's ability to achieve sustainable forest management are a concern. Increased damage by fire, pests, drought, and changing climate will certainly lead to shifts in species composition and distributions which may drastically affect forest productivity and management. The southern boreal forest is predicted to be severely affected by these changes and maintaining current species, ecosystems, and age-class distributions will likely not be feasible in this area (Hebda 1998). Some research predicts that the aspen parkland in the Prairie Provinces will grow at the expense of the current limit of the southern boreal forest (Hogg and Hurdle 1995). The persistence of the existing vegetation is relatively unclear, but many researchers believe that disturbance by fire, diseases, insects, or harvesting will be a major catalyst for species replacement causing changes in overall forest productivity in the southern boreal forest fringe.

Forest Fires

Fire is an integral part of the boreal forest ecosystem, over time it creates a rich mosaic of boreal forest communities composed of a variety of age classes. This in turn creates the underlying basis for plant and animal biodiversity within this biome (Weber and Stocks 1998). Fire aids in nutrient cycling, eliminating pest infestations, diseased areas, and increases forest productivity by burning old growth, dead standing trees and opening up that area to new growth. Many boreal forest tree species have evolved with fire and this ecosystem process is crucial to their continued survival. Jack pine for example, is retained after fire on the landscape and provides the strongest example for adaptation of a tree species to the periodic passage of fire (Weber and Stocks 1998). It has developed serotinous cones which release seed after a fire has passed through a region, thus regenerating the jack pine stand. This species has the potential to actually disappear as a natural component of the boreal forest landscape in the absence of fire (Weber and Stocks 1998).

It is very likely that fire will increase under warmer and drier conditions predicted for many areas of the boreal forest under climate change (Wotton et al. 2010). This is especially important because fire has the ability to rapidly change the forest at a landscape level (Hogg et al. 2002a). In remote areas, most forest fires are ignited by lightning and spread rapidly during periods of drought.

Since 1970, the average area burned by forest fires has doubled, despite improvements in technology, fire detection, and suppression (Hogg 2002). The ability of people to stop fire in the boreal forest will continue to be limited, except for small intensively managed areas. In Canada, there are an average of 10,000 fires each year, burning between one and eight million hectares annually (Hogg 2002). On average, area burned in Canada is expected to increase by 74-118% (Flannigan et al. 2002). A more recent study by Wotton et al. (2010) suggest an increase in fire occurrence of 25% by 2030 and 75% by the end of the 21^{st} century using the Canadian Climate Center GCM scenarios, while, the Hadley Center GCM scenarios suggest fire occurrence will increase by 140% by the end of this century. Under a doubling of CO_2 scenario area burned was shown to increase in Canada by 44% due to an increase in Seasonal Severity Rating (Flannigan and Van Wagner 1991). Balshi et al. (2009b) used a multivariate adaptive regression spline approach to assess the response of area burned to changing climate in the western boreal forest and found that average area burned per decade will double by 2041-2050 and increase on the order of 3.5-5.5 times by the last decade of the 21^{st} century. The potential losses of the timber, pulp, and paper production, as well as the damage to health and non-timber forest products caused by elevated fire activity are quite uncertain as much of the fire damage is expected to occur in more northern, less-accessible, regions (Kirilenko and Sedjo 2007).

Increased fire frequency has also been predicted over the southern boreal forest in central Canada, and this will probably promote vegetation change from the present mixed-wood forest of aspen, poplar, birch, spruce and pine to an aspen/grassland mosaic presently bordering this forest (Flannigan et al. 1998). The southern edge of the boreal fringe will likely be affected earliest and most drastically (Davis and Zabinski 1992). Many boreal species are adapted to fire, however proper regeneration requires that the trees be old enough to bear cones. Therefore, if the fire frequency increases and the fire return interval becomes shorter than the time for seedlings to reach sexual maturity, many species could be eliminated from their current range (Hogg and Bernier 2005). In upland areas currently dominated by white spruce, this could lead to an increase in aspen in high fire regions even if there is sufficient moisture for conifer establishment. The conversion of forest from conifers to aspen could lead to an eventual decrease in fire activity over time even under warmer and drier conditions. Aspen forests are often less prone to fire relative to conifers (Campbell and Campbell 2000; Campbell and Flannigan 2000) and have the ability to resprout following a burn, making this species well-suited under future climate scenarios. Forest management activities may need to take into account a probable increase in aspen forests on some parts of the landscape and timber supplies may have to be redirected toward aspen harvest.

Therefore, some components of the boreal forest ecosystem are extremely sensitive to damage by fire, which is predicted to increase under future climate. In addition, current adaptive capacity is low as indicated by the fact that area burned has increase since the 1970s despite improvement in detection and suppression technology.

Fires and Forest Health Damaging Agents

Fire does not influence the forest in isolation but rather it interacts with many other disturbances (Flannigan et al. 2000). Fire and insects are intrinsic and often synergistic components of many boreal forest ecosystems in North America, often interacting to affect succession, nutrient cycling, and forest species composition (McCullogh et al. 1998) and can have significant consequences for forest productivity and biological diversity. In addition, severe drought coupled with insect or disease infestation can also lead to extensive fire and mortality of boreal trees. Extensive mortality of aspen groves due to drought, insects, disease and fire occurred across the aspen parkland in 1961 (Zoltai et al. 1991) and again following the 1988 drought (Hogg and Hurdle 1995). The area affected by fire was exacerbated by dry conditions in 1989 when fires burned over 3 million hectares of boreal forest in northern Manitoba (Hirsh 1991) while in Saskatchewan the 1989 fire lead to a replacement of jack pine stands with aspen and grassland in some areas (Hogg and Hurdle 1995). These types of events can be expected to increase in the future and have the most drastic effects on the edge of the southern boreal forest and forest productivity in this region.

Episodic outbreaks of defoliating insects can affect the likelihood of fire ignition, fire behavior and intensity, and resulting post-fire species composition (McCullogh et al. 1998). The likelihood and severity of forest fire can be increased by feeding bark beetles, defoliating Lepidoptera, and other groups of insects that can alter the accumulations and distribution of fuels and vegetation. For example, outbreaks of mountain pine beetle in senescing lodgepole pine stands result in large fuel buildups and these outbreaks are often followed by intense wildfires which open serotinous lodgepole pine cones, eliminate overstory vegetation, and expose mineral soil. This allows the site to be reestablished by lodgepole pine and ensures the continued roles of mountain pine beetle (Amman and Schmitz 1988). A similar relationship can be found with jack pine budworm and fire. Jack pine stands generally sustain a jack pine budworm outbreak for 6 to 10 year intervals (Volney and McCullogh 1994). In the absence of fire, jack pine would likely be replaced by more shade- tolerance species (Nealis and Lomic 1994). However, budworm defoliation usually causes a buildup of dead dry needles cast off by larvae, some tree mortality, and “top-killed” trees, especially in over mature stands. These conditions encourage ground fires that can develop into crown fires if the canopy is contiguous (McCullogh et al. 1998). The fire opens jack pine cones and allows the seeds to fall on a newly exposed mineral seedbed, propagating a young, often dense jack pine stand to occupy the site once again. Under an increased fire interval, these evolved self-sustaining tree-insect mechanisms could possibly break down if the fire interval occurs before young stands have the chance to reach a reproductive stage. In this case, these pine stands are likely to be replaced by surrounding vegetation. In the case of the southern boreal forest and aspen parkland regions, pines could be replaced by aspen or grasses under an increased fire interval. This would cause a decrease in overall timber supply for this area.

Fire can also predispose trees to attack by bark beetles or wood-boring insects, as trees scorched or wounded by fire are weakened and less resistant to bark beetle attack. Influencing the abundance or species diversity of insect groups, and may affect quality and foliage for plant feeding insects (McCullogh et al. 1998). In some cases prescribed fire can also be used as a control mechanism, by killing insects directly or by altering soil properties, overstory or understory vegetation, tree density, or other aspects of their habitat (Mitchell 1990). This technique is especially useful if the insect pest spends a part of their life cycle in a vulnerable state on the ground (McCullogh et al. 1998) as most insects have evolved their own strategies for surviving fire or re-colonizing burned areas (Mitchell 1990;

Richardson and Holliday 1982). It is difficult to predict the interacting effects that fire and insects will have on the southern boreal forest in the future, but some basic assumptions can be made. Insects and fire are both predicted to increase on the boreal landscape, and the southern boreal forest will not be exempt from these factors. These two agents of change will likely act as a catalyst, by removing any remaining maladapted species on the landscape and facilitating the actual change in species composition (boreal to grassland shift). Insects will act in concordance with fire to increase the suitability of trees to fires and vice versa, making this region especially sensitive to these factors. Humans have a limited ability to prevent insect and fire disturbance when climatic conditions are favorable.

Regeneration

According the current climate change predictions, the southern boreal forest in central Canada will be affected by increased temperatures and a changing precipitation regime which will most likely lead to an increased risk of drought, extreme weather events, and subsequently a higher risk of fire, and pest damage. As discussed previously, this will lead to an increase in damaged forest area and therefore an increase in forest area in need of regeneration under less favorable climatic conditions. Forest regeneration is the act of renewing tree cover by establishing young trees naturally or artificially, promptly after the previous stand or forest has been removed. Forest regeneration includes practices such as changes in tree plant density through human-assisted natural regeneration, enrichment planting, reduced grazing of forested savannas, and changes in tree provenances/genetics or tree species (IPCC 2011). In addition to the traditional objectives of stand productivity and quality, improving forest resilience with respect to abiotic and biotic stresses will become a crucial objective (Future Forest 2011) of forest regeneration by forest managers. This may require a reassessment of current regeneration strategies and techniques as decisions made by forest managers during the regeneration phase can only be corrected later at a greater cost. This means that careful selection of regeneration strategies, methods, and materials are increasingly important during times of risk (Future Forest 2011), especially selection of tree species and provenance which may be better adapted under future climate conditions.

Natural Regeneration:

relying on natural seed sources or sprouting and little human intervention (e.g., seedbed preparation, selection)

(Future Forest 2011)

There are two ways in which a forest area can regenerate: **natural regeneration** or artificial regeneration.

Natural regeneration requires the presence of a nearby seed source in order for regeneration to occur. Natural regeneration helps preserve locally adapted populations, high genetic variability, good adaptation to micro-sites, undisturbed root development, low cost and low risk investment (Future Forest 2011). The problem with natural regeneration under climate change is that many species are predicted to become maladapted to their current locations and therefore natural regeneration would only exacerbate this problem as natural regeneration does not allow drastic change to the genetic stock. On the southern edge of the boreal forest, drought will most likely restrict germination of seeds or cause seedling mortality, causing natural regeneration to fail under drier climates. The most critical period during the life cycle of trees is during the first few weeks of seedling development (Daniel et al. 1979). In naturally forested regions, moisture deficiency frequently reduces the rate of germination, photosynthesis, and survival of conifer seedlings under current conditions. Dry climates prevent conifer regeneration from seed, usually due to lack of moisture or extended dry periods of time when the seedling first emerges (Hogg 1994). Therefore, natural regeneration may be significantly affected by climate change and the likelihood of trees reaching the free-to-grow stage will decrease. This in turn will affect the future development of the stand, the final volume at harvest and consequently impacting revenues available for reforestation and industry (Johnston et al. 2010b). Other disadvantages of natural regeneration include irregular regeneration density and tree species composition, the dependence on fructification and seed production, low flexibility and a long risk period (Future Forest 2011). Many species will respond differently in their ability to naturally regenerate under climate change. White spruce, aspen, lodgepole and jack pine will be discussed in the following sections with regards to natural regeneration under climate change.

White spruce

In many areas, white spruce trees are highly tolerant to drought as many survive on shelterbelts and block planting on the Canadian prairies and parkland regions. However, conifer seedling establishment requires a sustained period when soils are moist, a rare occurrence under a prairie-like climate (Hogg and Bernier 2005). The seedlings are the most vulnerable during the first few weeks following germination, even under brief periods (7-24 days) without rain may lead to high mortality (Phelps 1948). White spruce regeneration is often impeded by a lack of vegetative regeneration, it is the most vulnerable species to be lost from a site after fire because it must regenerate from seeds that disperse into the burn area from adjacent trees (Chapin III et al. 2004). In most natural stands, white spruce does not begin to produce seed in quantity until 30 years of age. It has the possibility to be eliminated from the boreal landscape if fire occurs more frequently than every 40-50 years (Moss 1932; Nienstaedt and Zasada 1990). The present climate of the southern parkland and grassland is too dry to permit natural regeneration of white spruce and other conifers. In a study by Hogg and Schwartz (1997) looking at white spruce regeneration along a climate moisture gradient extending from the boreal forest, across the aspen parkland, to the semi-arid prairie grassland, they discovered that natural regeneration was highest in the moist boreal sites and northern aspen parkland, decreased in the southern parkland and was negligible in the grassland region. If increases in atmospheric CO_2 lead to a drier future climate in the southern boreal forest of western Canada, similar to the current grassland regions, the ability of conifers to regenerate naturally may be significantly reduced (Hogg and Schwartz 1997). Under the absence of effective regeneration, conifer stands will be prone to replacement by aspen or grasses following fire or another type of disturbance (Schwartz and Wein 1992)

Aspen

A critical feature of aspen is its vegetative mode of reproduction which allows it to resprout vigorously following fires of low severity or from top-killed clones following drought. This mode of regeneration can allow aspen to survive in areas burned as often as 3 years (Peterson and Peterson 1992) and may explain its more southern distribution into the parkland and prairie regions of central Canada. Although aspen is prone to episodes of crown dieback following periods of drought, especially in combination with other stressors such as spring thaw-freeze events, insect defoliation and fungal pathogens (Hogg et al. 2002b) it is also highly adapted to these stressor because of its ability to regenerate vegetatively following mortality of its above ground stems. Notwithstanding, aspen die-off is already occurring across North America and many believe that climate change is to blame. On the hillsides of Arizona to the peaks of Idaho, aspen trees are failing by the tens of thousands (Ricciardi 2009). **Sudden aspen decline** has also been observed in Colorado starting in 2004, and by 2008 over 220,000 ha, 17% of the aspen cover in the state, was affected. Sudden aspen decline has lead to loss of aspen cover and is occurring in areas where early loss of aspen due to climate change has been predicted (Worrall et al. 2010). Preliminary evidence shows that affected stands may fail to produce suckers in response to crown loss and mortality, and this is mostly likely due to moisture stress as an underlying factor (Worrall et al. 2008). Similar effects have been seen in the aspen parkland and southern boreal forest of Alberta and Saskatchewan, where branch dieback, growth loss and mortality of aspen have increased following a severe drought in 2001-2002 (Hogg et al. 2008). Worrall et al. (2010) believes that a number of compounding factors such as location, physiological maturity, low stand density, drought and high temperatures during the growing season, insects and pathogens outbreaks attacking stressed trees all provide reasons for this large scale dieback.

Sudden Aspen Decline (SAD) : *this disease is characterized by rapid, synchronous branch dieback, crown thinning and mortality of aspen stems on a landscape scale, without the involvement of aggressive, primary pathogens and insects*

Lodgepole and Jack pine

Lodgepole pine and jack pine are the northern-most pines in the boreal forest of North America and are both located in the central part of Alberta (Rweyongeza et al. 2007a). Where these two species meet they hybridize and the resultant trees resemble lodgepole pine rather than jack pine. Both lodgepole pine and hybrids occur on more mesic sites and therefore have the potential for higher elevational populations on sites in proximity to each other, whereas jack pine has a more scattered distribution on xeric sandy sites and occurs more often in pure stands (Natural Regions Committee 2006). Jack pine is a species well adapted to fire in the forest environment and this is exhibited by its cone serotiny which releases seeds after a fire has passed through an area. Without the periodic passage of fire, jack pine would disappear from the landscape (Cayford and McRae 1983). However if climate change leads to increased fire frequencies in the southern boreal forest and parkland regions, conifers could be gradually eliminated if they are burned before reaching seed-bearing age (ca. 30 years), or if soil conditions become too dry for successful seedling establishment (Hogg 1994; Hogg and Hurdle 1995). Dry conditions are also know to exacerbate fire and in the Nisbet Forest, located 100 km north of Saskatoon, Saskatchewan, poor regeneration of jack pine occurred following the 1989 fire and has led to the conversion to aspen and grassland in some areas (Hogg and Hurdle 1995). Lodgepole pine on the other hand has shown range expansion activity at the northern edge of its range. Johnstone and Chapin (2003) document the range expansion activity of lodgepole pine into a relatively pristine natural environment in the Yukon, perhaps in relation to climate warming.

Assisted Migration (managed relocation) : *the practice of deliberately populating members of a species from their present habitat to a new region with the intent of establishing a permanent presence there, generally in response to the degradation of the natural habitat due to human action (e.g., climate change) (Wikipedia contributors 2011a).*

Artificial regeneration is the active introduction of seed or plant material to a forest site, and allows for prior selection of the reproductive material with respect to certain objectives of plant breeding or genetic improvement (Future Forest 2011). This method relies on seeding, planting of seedlings, or planting of cuttings, and was first established to improve tree growth, quality, and resilience to pests, drought and disease. In artificial regeneration, it is important to use seed sources adapted to their plantation environments for reforestation. This has long been practiced based on observational differences among populations within species for survival, growth, and resistance to biotic and abiotic stresses (Wang et al. 2006). Presently, forestry managers that practice artificial regeneration often go by the assumption that "local is best" which assumes that offspring planted locally for reforestation are going to experience a climate similar to that experience by their parents, and grandparents and more distant ancestors. This is increasingly unlikely due to climate change (Wang et al. 2006) and new strategies must be developed. Artificial regeneration may still offer the best option for managed forest areas across the southern boreal forest to deal with climate change. As noted earlier, plants are expected to fall behind the shifting climate because their migration rates will not be fast enough to keep up with predicted temperature and precipitation change (Iverson and Prasad 1998; Iverson et al. 2004; McKenney et al. 2007). In the eastern United States, less than 15% of new potential habitat would have even a small probability of being colonized within 100 years. This problem will be exacerbated in rarer species because of low source strength (Iverson et al. 2004), making them more prone to extinction (Schwartz et al. 2006). In order to maintain forest cover in the island forests and areas of the southern boreal fringe under climate change, new provenances and exotic species maybe need to be considered as potential regeneration species. Species that are better adapted to warmer, drier conditions could be considered as regeneration options by current forest managers in anticipation to climate change; this approach to regeneration is known as **assisted migration**. This raises important policy challenges regarding introduction of new provenances or exotic species and their use in forest regeneration (McLachlan et al. 2007). The concept of assisted migration directly subjugates the ideals of conventional conservation biology approaches that attempt to establish or reestablish habitat corridors to allow species to disperse in response to climate changes. Many scientists oppose the idea of assisted migration as a conservation strategy as past occurrences of introduced species outside their native ranges can often be associated with negative ecological and economic impacts (e.g., Zebra mussels (*Dreissena polymorpha*), leafy spurge (*Euphorbia esula*) and Asian gypsy moth (*Lymantria dispar*). In Ricciardi and Simberloff's (2009) synthesis of the human legacy of damage through species introductions, they argue that ecologists do not know enough to engage in the practice of assisted migration without causing harm to associated communities (Schwartz et al. 2009). However, it is important to consider assisted migration in the face of a changing climate given the rapidity by which habitat and climate is predicted to change and the simple fact that species will not be able to keep pace even under the best circumstances. Assisted migration is a huge topic of debate that cannot be discussed in its entirety in this report; however, it needs to be noted as a potential regeneration strategy under future climate change. We must be careful to engage this practice with the proper respect for ethical, legal and biological issues surrounding the idea of managed relocation and determine if it is the proper strategy to use on a case by case basis. The Canadian Forest Service is preparing a comprehensive review of the ecological, legal and ethical aspects of assisted migration which will be completed by the end of 2011.

Assisted migration and other methods of artificial regeneration will not be cheap. Artificial regeneration often requires a lot of resources to implement, including: the presence of seed orchards or stands, a seedling nursery, a labor force and usually site preparation, and equipment (Future Forest 2011). These additional resources could potentially increase in cost under future climate change as forests may become less productive and more difficult to renew after disturbances. Warmer temperatures and drought stress predicted under climate change will increase the difficulty in reforestation following harvest. Light and water are the two most important abiotic determinants of successful seedling establishment (Desteven 1991), and water may become a limiting agent in many boreal regions. New silvicultural methods may need to be used to compensate for lower moisture availability by: increasing seedling densities to compensate for increasing seedling mortality, bringing in exotic species that are more drought tolerant (assisted migration), planting larger/older seedling, and using different or more intensive site preparation methods to counteract the effects of drought.

Seedlings are especially sensitive to short term drought events, and drier weather patterns can cause decreased survival rate in seedlings. One option by forest companies may be to plant trees at higher densities in order to compensate for increased seedling mortality. This will ultimately increase the cost of regenerating sites after harvest as companies will need to invest in more seedlings or cuttings per area. The same is true for planting larger and older seedlings; each seedling will be associated with a larger cost due to the increased time taken to grow the seedlings. For example, one year old seedlings of white spruce are $1.69 per tree, while two year olds are $2.49 per tree (Rimbey Trees 2009).

Methods including more site preparation or longer periods of vegetation control, may need to be used to increase the probability of trees reaching the ‘free to grow’ stage. Cortini et al. (2011) found that site preparation and vegetation control can be used to mitigate climate change effects on early plantation growth in boreal forests. This is especially true for conifers which are extremely susceptible to competing vegetation during early stages of their establishment because the seedlings are small and generally slow growing. By implementing application of proper site preparation the negative impact of climate change can offset

Artificial Regeneration: relies on the active introduction of pre-selected seed or plant material to a forest site

(Future Forest 2011)

drought stress by decreasing competition from tall shrubs and grass, improve soil temperature, reduce limitations from excess spring moisture, increase nutrient availability and accelerate early root growth under the right conditions (Cortini et al. 2011). Mechanical preparation and vegetation control may soon be required to achieve regeneration following harvest of trees, especially in areas under moisture stress (i.e. southern boreal forest). Therefore, costs associated with replanting after harvest can be assumed to increase under climate change as more intensive work may be needed to ensure trees become established. This increase in cost will likely affect forestry companies who are responsible for replanting trees following harvest.

Existing forests are moderately resistant to climate variability; however it is the forest regeneration phase that will be most susceptible to the changed climate. Thinning or selectively removing suppressed, damaged or poor quality trees may help to increase light, water and nutrients available for the remaining trees (SES 2011). However, there are practical limitations to implementing many of these changes into forestry practices. At the scale of the Canadian or even or southern edge of the boreal forest, the costs of intervening at such a large scale would likely be prohibitively high, while implementing all or some of these activities would contribute to companies having to spend more time and money to get trees established and growing as compared to current practices.

Regeneration Lag

Regeneration lag is the time (number of growing seasons, expressed in years) following harvest required for a new stand of trees to initiate growth as compared to the natural yield curve. It is equivalent to the time a harvested area remains fallow without regenerating trees (Sustainable Resource Development 2008). Due to the potential increase in difficulty in regenerating stands after harvest, longer rotations may begin to occur. This in turn will lead to companies having to postpone harvesting, which will cost them money and could potentially increase difficulty during forest management planning. The current assumption in Alberta is that a two year regeneration lag could increase to five years or more with climate change (Fraser 2011).

Tree Growth

Climate change is highly likely to impact forest productivity over the next century. The direction and degree of change are uncertain due to many factors changing simultaneously, including atmospheric composition, temperature, rainfall, and land use (Medlyn et al. 2001). Net Primary Productivity (NPP) is a quantitative measure of the carbon fixed by plants per unit time and space (Liu et al. 2002). It is the primary conduit of carbon transfer from the atmosphere to the land surface and is thus a fundamental component of the global carbon cycle (Kang et al. 2006). In other words, NPP is a measurement of plant growth obtained by calculating the quantity of carbon absorbed and stored by vegetation. Direct measurements are difficult to conduct, destructive, time intensive and costly. Therefore, most large-scale measurements of NPP are done through model simulation. Simulation results show that Canada's annual NPP was 1.22 Gt C year^{-1} in 1994, of which 74% was attributed to forests, mainly the boreal (Liu et al. 2002). Across this landscape NPP varied by ecozone and provinces/territories; the Boreal Plain ecozone had a mean NPP value of 321 g C m^{-2} year^{-1} (Liu et al. 2002). The vegetation responses to climate change, which ranged from ecophysiological responses to ecosystem carbon balance, can lead to net changes in NPP (Chiang et al. 2008). These impacts include the potential fertilization effects of increasing CO_2 levels, regional fire activity, drought, insects, water use efficiency (WUE), nitrogen mineralization, and elevated temperatures. Kang et al. (2006) showed that the North American boreal ecosystem has been sensitive to historical patterns of increasing atmospheric CO_2, climate change and fire. They found that the relative impacts of disturbances and **evapotranspiration** (ET) interact in complex ways and are spatially variable, while historical trends of increasing atmospheric CO_2 resulted in an overall increase in annual NPP of 13% within a 350,000 km^2 portion of the Canadian boreal forest. Fire activity reduced NPP and ET, and drier areas of the forest were subject to more fire, causing larger decreases in NPP. In the northern high latitudes of Canada, satellite remote sensing was used by Zhang et al (2008) to detect recent climate driven changes in vegetation. Results showed some key impacts on NPP: low temperature constraints on Boreal-Arctic NPP are decreasing by 0.43% per year and there is an increasing moisture constraint of 0.49% per year which is offsetting the potential benefits of longer

Evapotranspiration (ET) : *defines the land-atmosphere exchange of water and is the primary interface between terrestrial energy and water cycles and is also closely linked with NPP and the carbon cycle through vegetation canopy stomatal controls for both CO_2 and water vapor (Kang et al. 2006)* growing seasons. These findings show that drought can induce NPP decreases, resulting in a reduction of carbon accumulation, and this will likely occur more frequently in a warmer and drier climate. The multitude of effects causing changes in NPP under climate change will vary by species, region, and site.

Climate change is predicted to have many positive effects on forests. According to simplistic growth scenarios, tree productivity depends on site fertility, temperature, and precipitation. An increase in temperature would result in accelerated growth by lengthening the growing season and reducing the frequency of summer frost in northern regions (Bernier 2011). Elevated temperatures may enhance metabolic photosynthesis and increase nutrients available in the soil through increased decomposition rates. A longer growing season under warmer temperatures in the spring and fall could also allow trees to accumulate more annual growth in high latitude systems. Earlier spring development has occurred in parts of Europe where an analysis of Europe's International Phenological Garden data gathered from 1959-1993 reveals a lengthening of the growing season of 10.8 days since the 1960s (Menzel and Fabian 1999). Relationships between temperature and flowering for trembling aspen, Saskatoon berry (*Amelanchier alnifolia*) and chokecherry (*Prunus virginiana*) in the area of Edmonton, Alberta for 1936-1998 show a trend towards earlier flowering (Beaubien and Freeland 2000). However, elevated temperatures may also decrease NPP by decreasing soil moisture and enhancing respiration (Peng and Apps 1999). In as early as 2030-2039, Rweyongeza et al. (2007b) predicted that warming temperatures could cause serious declines in survival and growth of white spruce in Alberta. Warming would intensify drought conditions in northern and central Alberta making it difficult for white spruce to attain substantial survival and growth.

Enhanced WUE in both the short and long term should occur under increasing CO_2 concentrations. Trees will not have to open their stomata as frequently, through which they gain CO_2 and transpire water vapor. In addition, they tend to produce fewer stomata per unit area of leaf surface under higher levels of CO_2 (Long et al. 2004). These changes reduce the loss of water by transpiration, and the amount of carbon they gain per unit of water lost typically rises. This may affect local adaptation in drier locations (Aitken et al. 2008), helping trees exist in drier climates by increasing their ability to withstand drought. This means that drought stressed areas and subsequent decrease in productivity may be partially counteracted by the concurrent rise in CO_2.

The primary effect of the response of plants to rising atmospheric CO_2 is to increase resource use efficiency (Drake et al. 1997). Improved soil-water balance, increased carbon uptake in the shade, greater carbon to nitrogen ratio, and reduced nutrient quality for insect and animal grazers are all possibilities that have been observed in field studies in response to increases in CO_2 (Drake et al. 1997). White spruce in Saskatchewan showed an increase in productivity of about 40% with adequate moisture, and a 60% increase when WUE was increased using the PnET ecosystem simulation model (Johnston and Williamson 2005). In terms of direct increases in plant productivity, it has been noted in many experimental studies that C_3 photosynthesis responds strongly to CO_2 concentrations, with photosynthesis increasing by 25-75% with a doubling of atmospheric CO_2 concentrations (Cure and Acock 1986; Drake et al. 1997; Kimball 1983; Urban 2003). Peng and Apps (1999) used a process-based ecosystem model (CENTURY 4.0) to investigate the patterns of NPP along a transect across the boreal forests of central Canada and the influence of climate change, CO_2 fertilization and fire disturbance regions on changes in NPP. The model showed that climate change led to increased NPP for most sites, mainly due to an increase in CO_2. However, many of these studies do not account for maladaption arising from a changed climate, basing their predictions on productivity-climate relationships or process-based models developed from adapted populations, or requiring populations to migrate to adapt at a pace sufficient to allow them to thrive in the face of rapid climate change, a scenario that appears untenable (Davis and Shaw 2001; Rehfeldt et al. 1999).

Experiments have been done in closed or open top chambers and shown a high potential for CO_2 to enhance growth in trees, such as a 70% increase in biomass production of orange trees (Kimball et al. 2007). The free-air CO_2 enrichment (FACE) experiments showed a smaller effect of increased CO_2 concentration on tree growth. Long term results from a FACE experiment in Switzerland show an average net primary production increase of 23% (range 0-35%) in response to a doubling of CO_2 in young trees, but little response in mature trees (Korner et al. 2005). A meta-analysis of tree growth among a number of forest FACE sites showed an average increase of 23% in woody biomass (Norby et al 2005). However, it is still unknown what the net effect will be in the field without the size limitations of the chambers; it may only cause an increase in productivity for the short term, with decreases eventually occurring due to acclimation, soil nutrient or moisture limitations (Millard et al. 2007). Scaling up measurements from leaves and individuals to stands and ecosystems may introduce significant error and this has led some to conclude that elevated CO_2 may not affect stands in the same way that single individuals are affected (Peng and Apps 1999). Much of the preliminary works shows that increases in CO_2 concentrations may help trees to deal with increasing temperatures and drought effects through gains in WUE, more efficient photosynthesis and carbon fertilization. These effects may help to offset some of the negative effects of climate change under the right conditions (e.g.: sufficient moisture and nutrients). Johnston and Williamson (2005) found that the effects of climate change on future stand yields was increased unless those stands experienced an extreme drought.

Increases in net nitrogen (N) mineralization are also positively correlated with changes in NPP (Peng and Apps 1999). Current productivity in boreal forest ecosystems is limited by N availability and low temperatures; therefore, NPP increases under climate change and increasing CO2 will likely be mostly influenced by the effectiveness of elevated temperatures in enhancing N availability (Peng and Apps 1999). Some studies predict that increases in nitrogen mineralization will cause increased productivity and growth for trees under climate change due to increasing temperatures. However, a study done in northern hardwood forests showed that net N mineralization and nitrification were slower in warmer, low elevation plots, in both summer and winter (Groffman et al. 2009). In summer, this pattern was due to lower soil moisture in warmer soils and in winter there was less snow which caused more soil freezing and reductions in N cycling. These results suggest that nitrogen will likely be limited under warmer temperatures predicted by climate change if moisture is insufficient. Therefore, the southern boreal forest may not see increases in N mineralization due to the decreases in moisture predicted for this region. Therefore, N limitations and soil fertility could limit the magnitude of the growth effects.

Overall, there are many positive effects predicted by climate change and its impacts on boreal forests. Most of these effects are shown to produce increases in NPP and overall tree growth. However, most of these benefits can be offset by increases in moisture stress. In the drought stressed regions of the southern boreal, some forests are already moisture limited, and in the areas of increasing drought stress at the southern edge of the boreal forest, many of these regions will not benefit from these positive effects. In addition, the multitude of negative effects such as difficult species migrations, increases in frequency and intensity of forest fires, drought, insect outbreaks and weather events will most likely overshadow any beneficial effects from climate change. Currently, Canadian forests show mixed signs of increases productivity. Recent growth analyses conducted on samples from sites located across the boreal forest suggest a great deal of variability in response to on-going climate change between species and regions (Bernier 2011).

Reduced Survival

Persistent changes in tree mortality rates can alter forest structure, composition, and ecosystem functions and services such as carbon sequestration (Van Mantgem et al. 2009). Tree mortality is often the result of both long-term and short-term stress (Van Mantgem et al. 2003), arising from complex interacting set of stressors. Often individual tree death will occur as a result on the interaction of many different long term and short term stressors, like multi year drought followed by insect attack. Recent warming events and drought stress have been implicated as contributing factors of increasing forest mortality. Evidence of this has been seen globally and is reviewed by Allen et al. (2010), who presented the first global assessment of recent tree mortality. Natural episodic tree mortality occurs in the absence of climate change; however, many studies have suggested that many of the world's forests are already experiencing vulnerability to climate change and this is exhibited by a higher background tree mortality rate and die-off in response to future warming and drought (Allen et al. 2010). In western North America background mortality rates have increased rapidly in recent decades, with doubling periods ranging from 17 to 29 years among regions (Van Mantgem et al. 2009). Mortality occurred in young trees and therefore the increase in mortality could not be solely attributed to aging of tree populations. Recent increasing temperatures and drought events have led to extensive insect outbreaks throughout North America over the last decade, affecting ~20 million ha and many tree species since 1997 from Alaska to Mexico (Allen et al. 2010). Bark beetle outbreaks in western North America has caused massive losses in forests (Breshears et al. 2005) including British Columbia where the B.C. Ministry of Forests, Lands and Natural Resource Operations estimates that the mountain pine beetle has now killed a cumulative total of 726 million cubic meters of timber since the infestation began (Ministry of Forests 2011). Drought has induced massive mortality of aspen in southwestern US and along the southern edge of the Canadian boreal forest (Michaelian et al. 2010). Aerial surveys of the boreal fringe revealed 35% dead biomass of aspen in areas of severe drought, while an annual forest health assessment from a regional network of aspen plots show a major increase aspen dieback and other trees. This trend has been noted since the early 1990s across Alberta and Saskatchewan (Hogg et al. 2002a; Hogg et al. 2006; Hogg et al. 2008). In 2001-2002, an severe regional drought across the prairies caused more than a two-fold increase in stem mortality and a 30% decrease in stem growth during and following the drought, showing that short term drought can severely affect aspen stands (Hogg et al. 2008). Recent warming events and consequently increases in water deficits, have been implicated as contributing to these episodes of elevated tree mortality (Van Mantgem et al. 2009).

Loss of Timber and Revenue

Global round wood production, including industrial wood and fuel wood, has been growing steadily from 2.5 billion m^3 in the 1960s to 3.2 billion m^3 in the 1990s. Modeling studies generally show an increase in global industrial production of round wood, with increases or decreases in prices in the future in the order of ±20% (Irland et al. 2001; Sohngen et al. 1999). This will not occur equally across the globe, a shift is predicted to occur between the temperate and tropical zones and between the Northern and Southern Hemispheres, with increases in production noted for the south and away from temperate and boreal forests (Sohngen et al. 1999). Sohngen and Sedjo (2005) suggest that climate change will lead to a net increase in global timber supply, although, some countries will gain more than others. In North America, climate change is predicted to significantly decrease economic benefits to producers and these decreases will be significant in the early 21st century (Sohngen and Sedjo 2005). It is also important to note that most of the wood that will be harvested in Canada over the next 50 to 100 years will come from trees that are already growing or from those that will be planted in the next decade, with minimal consideration of climate change impacts (Lempriere et al. 2008). In the western boreal forest, Lempriere et al. (2008) assessed some of the impacts of climate change on timber supply considering quantity, quality , and timing. They found that now and in the near future (2011-2040) timber supply will be positively impacted by climate change, although positive impacts will be slight. From 2041-2100 impacts will become negative, and timber supply will be reduced. Perez-Garcia et al. (2002) provided country-specific predictions of the market impacts of climate change up to 2040. Of the countries included in the analysis, Canada is the only one for which the impacts on producers are predicted to be negative. Moreover, these negative impacts are predicted to be substantial due to lower prices of timber, dieback of trees, and slower productivity increase because of long rotation species (Sohngen et al. 2001). The analysis suggests that Canada's producers of forest products are uniquely vulnerable to market impacts relative to their counterparts elsewhere in the world (Johnston et al. 2010b). At the same time, climate change may also have a dampening effect on prices of forest products in global markets due to higher growth rates and increase supply, particularly in developing countries (Sohngen and Sedjo 2005). Forests in these regions will react quickly with more productive short rotation plantations, driving down timber prices (Sohngen et al. 2001).

Several interrelated factors will determine the net impact of climate change on timber supply. Forest timber supplies can be reduced by increased fire or pest activity brought about by warmer temperatures and moisture stress, while these climatic factors may also cause limitations on tree growth. Other impacts such as climate change on forest land area, disturbance patterns, silvicultural activities, regeneration success, species composition and regulator constrains can also lead to changes in timber supply and forest sector profitability (Johnston et al. 2010b). At the local scale, effects on timber supply may be positive or negative, depending on location, time frame, and human adaptation (Johnston and Williamson 2005). Therefore, forest management planning and forest investments are important and forest managers should begin to give consideration to potential climate effects in long run planning (Spittlehouse and Stewart 2003). For industry, key considerations will be the degree to which changes in timber supply jeopardize fixed capital investments. If timber supply under climate change continues to meet the requirements of an existing mill over its life-span, then the net impacts may be relatively small, assuming that delivered wood costs do not increase significantly (Johnston et al. 2010a). Notable socioeconomic impacts will be felt where changes in timber supply occur over a short time that cause large swings in local timber supply (e.g., mountain pine beetle in British Columbia). This can result in changes in production and employment that may lead to increasing challenges for communities, forestry companies, and provincial and territorial revenues (Johnston et al. 2010a).

Climate change is already resulting in shorter winter harvest seasons due to a reduction in frozen ground. The depth of soil frost is dependent on air temperature and snow depth, as well as on soil characteristics (Venäläinen et al. 2001) and as temperatures warm, the amount of frozen soil decreases. Studies have also found that there is now 10% less frozen ground in the Northern Hemisphere than in the early 20th century and it is not freezing as deeply or as long (The National Snow and Ice Data Center 2011). In Finland, Venäläinen et al. (2001) predicted under a warming of 4-5°C, that there will be an overall decrease in the length of the soil frost period. However, though winters will be warmer, an associated decrease in snow cover in Southern Finland will result in increased frozen ground in the middle of the winter relative to now. The opposite seems true for forest companies in Saskatchewan which have already indicated that changes to seasonal harvest operations are already becoming troublesome. During the winter of 2005-2006, frozen-ground conditions did not occur until January and harvest operations had to be relocated to summer sites prior to that time (Johnston et al. 2010b). The ability to harvest timber in the winter is important in the boreal forest as conditions can be too wet during the summer for many regions. Harvesting operations have to be when soils are frozen to reduce impact on the environment and allow access to wetter areas. Increasing numbers of warmer winters and shorter seasons with frozen ground will affect harvesting, hauling and other forestry operations. This will increase costs and timely delivery of timber to the mill site, with more frequent road closures and impacts to infrastructure (Johnston et al. 2010a; PARC). Forest companies have few options to deal with decreases in frozen ground conditions. Flexibility in the harvest schedule will become increasingly important as frozen ground conditions become less reliable and extreme weather events (e.g., heavy precipitation, flooding) prevent access to some sites (Johnston et al. 2010b). In the short term, harvesting can be increased on summer ground, but eventually timber supply in summer-access areas will run out and many adaptation options are restricted by cost and legislation (Johnston et al. 2010b). Future projections for warmer winters and more early winter precipitation, which insulates the ground and limits freezing, suggest that the duration of frozen ground conditions will continue to shorten (Barrow et al. 2004). This has the potential to decrease revenues for forestry operations. Overall, any improvements in productivity resulting from enhanced growth because of climate change will probably not be able to offset the productivity that will be lost because of increased natural disturbances (Kurz et al. 1995). The impacts of climate change on timber supply are expected to be greatest in the short and medium term in the western boreal forest because of increased disturbance regimes and drought. The quantity and quality of fiber supply from aspen are also expected to decline in the southern boreal west, owing to increasing impacts of drought, insects, and fungal pathogens. The zone of greatest aspen productivity may move northward into more remote locations, creating challenges for the forest industry in terms of timber access and transportation costs (Lempriere et al. 2008).

Carbon Storage

The carbon cycle has long been recognized as important for understanding climate change and the influence of anthropogenic CO_2 emissions. Climate models that include terrestrial and oceanic carbon cycles simulate a positive feedback between the carbon cycle and climate warming, where increases in airborne CO_2 causes amplified warming which result in additional CO_2 released from systems (Friedlingstein 2006). Others argue that rising CO_2 levels will enhance sequestration above normal rates due to a fertilization effect (EPA 2011). However, the concurrent changes in temperature and precipitation, coupled with site specific nutrient availability complicate the issue. As stated earlier, the carbon fertilization effect may also be short lived or only beneficial to specific species. The boreal region is the world's largest **terrestrial carbon** storehouse comprising forests, wetlands, and peatlands, and therefore is important to consider in a changing environment. The Canadian boreal forest stores an estimated 186 billion tons of carbon in the forest and peat ecosystems, equivalent to 27 years worth of the world's carbon emissions in 2003 from the burning of fossil fuels (International Boreal Conservation Campaign). Most of the large carbon pool is in peatlands, which cover almost 2.6 million km^2. The carbon stored in this region is facing serious threats from industrial development and global warming. Therefore, it is not just important to mitigate carbon emissions, but to also preserve our carbon-rich forested regions, especially under a changing climate. Increased fires, insect outbreaks, warming of permafrost and peatland destruction are predicted to increase with global warming, thus accelerating the release of carbon currently stored in this system and creating a positive feedback loop. Direct human induced changes in the carbon stored in forests include management activities such as: harvesting, (a temporary loss of carbon from the landscape, and deforestation, a permanent loss of carbon. In 2006, almost 10,000 km^2 of harvest area extracted close to 45 million tons of carbon from Canada's forests. Because of the large amounts of carbon stored in older forests, this has had particularly negative effects on the carbon balance (Olsson 2010). Deforestation can increase carbon emissions and diminish storage capabilities. During discussions on the Kyoto Protocol, countries became interested in their national carbon stores by the possibility of being able to claim large sinks in their managed forests and gain so-called 'carbon credits' that could be traded on a global market.

Terrestrial Carbon:

Terrestrial carbon sequestration is the process through which carbon dioxide (CO_2) from the atmosphere is absorbed by trees, plants and crops through photosynthesis, and stored as carbon in biomass (tree trunks, branches, foliage, and roots) and soils. (EPA 2011)

This along with Canada's commitment to reach a goal of reducing carbon emissions below 1990 levels by 2012 has caused a rising interest in boreal forest carbon stores. Currently, analysis done by the Carbon Budget Model of the Canadian Forest Sector (Kurz et al. 2009) has projected that the managed forests of Canada could be a source of carbon between 30 and 245 Mt CO_2e yr^{-1} during the first Kyoto Protocol commitment period (2008-2012). There has been a recent transition from source to sink due to the large insect outbreaks that have affected Canadian forests (Kurz et al. 2008b). SRD has identified carbon storage as an important ecosystem service with a medium vulnerability to climate change (Sensitivity = low; Adaptive Capacity = low) (Table 6).

Table 8: Degree of sensitivity, adaptive capacity and vulnerability of Alberta's forests to impacts of climate change on Carbon Storage (H=High; M= Medium; L= Low)

Ecosystem service	Key projected Climate Change impacts	Vulnerability Assessment		
		Degree of Sensitivity (H/M/L)	Degree of Adaptive Capacity (H/M/L)	Vulnerability (H/M/L)
Carbon Storage	Soil moisture declining below bioproductive levels	L	L	M

Exposure

As previously discussed, the global climate is expected to change due to increased atmospheric concentrations of greenhouse gases, especially in the boreal region where summer temperatures are predicted to increase by about 1-2°C in the summer and 2-3°C in the winter (Mäkipää et al. 1999). These elevated temperatures could lead to an increase in NPP (Gower et al. 1994), as well as to accelerate decomposition of soil organic matter (Peterjohn et al. 1994). Under climate change, evapotranspiration may increase more than precipitation, limiting tree growth especially on soils with low water holding capacity (Kellomaki and Vaisanen 1996), although increase water use efficient may play a part in compensating for this loss of water. Increases in insects, fires, and other natural disturbances will also play a part in influencing the carbon storage ability of the southern boreal forest. Loss of forest area predicted by shifts in species moving northward, especially for the boreal transition zone, could cause massive loss in carbon storage if this ecosystem becomes converted into grassland.

Sensitivity

Forest are often assumed to be a large sink for atmospheric carbon in the changing environment (Fancey et al. 1995; Tans et al. 1990),with a sink estimated to be 0.4-0.6 Pg C per year (Apps et al. 1993; Dixon et al. 1994) but the opposite is also true (Goulden et al. 1998). There has been a significant amount of work done attempting to understand how projected climate changes will affect the carbon stored in the world's terrestrial biomes. Four natural processes have been identified which control the storage and release of C in boreal forests, and they include (1) the rate of plant growth, (2) the rate of decomposition of dead organic matter, (3) the rate of frozen soil formation, (4) the frequency and severity of fires (Kasischke et al. 1995). These four processes will be discussed in terms of climate change.

Rate of plant growth

Carbon stored for long periods of time (decades to centuries) is considered sequestered (Wayson et al. 2009). Due to growing trees which uptake CO_2 during the respiration process, this gas is not accruing in the atmosphere at a rate equal to fossil fuel burning, which has helped mitigate climate change. Free-Air CO_2 Enrichment (FACE) experiments propose that rate of tree growth could increase with rising levels of CO_2 in the atmosphere, but these effects may saturate overtime as trees adjust to increased CO_2 levels. Any alteration in tree growth rates, whether it is positive or negative, will have an influence on rates of carbon storage. Increases in forest growth, would increase carbon sequestration and remove more CO_2 from the atmosphere, creating a negative feedback system that lessens climate change. Losses of carbon through decreased growth rates would result in less carbon uptake, and this may possibly occur in the southern boreal forest, prairie parkland and island forest regions of western Canada as warmer and drier conditions are predicted to decrease tree growth or eradicate trees altogether. The IPCC (2007) predicted that a net carbon uptake by terrestrial ecosystems is likely to peak before mid-century and then weaken or even reverse, thus amplifying climate change. It is also important to note that old growth forests also sequester carbon. For years, it was thought that mature forests were in equilibrium, reaching a max capacity for a given climate and physiographic setting. Recent studies suggest that mature forest carbon sequestration is underestimated and that autotrophic respiration decreases with increasing age, allowing mature forests to maintain a carbon sink (Carey et al. 2001; Lavigne and Ryan 1997).

Temperature is a limiting factor in boreal forests; therefore, it might seem reasonable to assume that moderate levels of warming would be beneficial for tree growth. Currently, some recent studies have shown increases in tree productivity due to longer growing season and warmer temperatures in the southern boreal forest. Chen et al. (1999) found that an old aspen site in Prince Albert National Park, Saskatchewan (BOREAS study) was able to sequester significantly more carbon due to warmer spring temperatures. In 1994, spring temperatures were 4.8°C warmer than 1996, allowing the trees to have earlier leaf emergence, longer period of productivity, and sequester an additional 70 ± 30 g C m^{-2} per year. Griffis et al. (2003) studied three southern boreal old growth forests in Saskatchewan and Manitoba and found a similar trend over a 5 year El Nino period. The old aspen site located in Prince Albert National Park, had warmer spring temperatures, enhanced annual carbon sequestration, and an increased carbon sink strength by 180 g C m^{-2} per year. Six years of eddy covariance data at the BOREAS southern old aspen site also indicated that carbon sequestration at boreal aspen sites may benefit from warmer climatic conditions because respiration is relatively conservative and photosynthesis increases in response to a longer growing period (Griffis et al. 2003). The old aspen sites were also compared with black spruce and jack pine sites, and although the aspen had the shortest growing season, it represented the greatest carbon sequestration due to its relatively large photosynthetic capacity (Griffis et al. 2003). Therefore, if aspen increases on the landscape as predicted by many climate change studies, warmer temperature and longer growing seasons may be beneficial to aspen. It has the ability to sequester more carbon relative to other stand types and this may help mitigate additional CO_2. Aspen stands currently make up 15% of the land cover in the southern boreal forest. Although this is a small percentage, they play a large role in regulating the local climate by reducing the water pressure deficit and temperature of the convective boundary layer due to greater water loss from transpiration (Griffis et al. 2003). This system has important implications for carbon cycling in the southern boreal because under drier conditions it is likely that the photosynthetic efficiency and carbon fixation would decrease in these aspen stands due to this species' strong sensitivity to decreasing soil water content (Griffis et al. 2003; Hogg et al. 1997; Hogg et al. 2000). Black spruce stands in the southern boreal forest demonstrated a larger photosynthetic capacity relative to aspen, however, its annual overall carbon sequestration was smaller because greater respiration occurring mid-season (Griffis et al. 2003).

However, the argument for warmer temperature increasing growth rates is not unequivocal. Higher temperatures over the last few decades have increased and decreased tree growth depending on site, location and other impacting factors, such as drought stress. Negative effects on tree growth may become widespread as global warming increases. There is now evidence suggesting that these terrestrial carbon sinks are becoming saturated as global reforestation rates have been slowing, while other studies show that forest productivity at a high level of CO_2 slows after an initial increase, and productivity returns to levels at or below historic rates (Lichter et al. 2008; Wayson et al. 2009). Other studies even predict that boreal forest dieback could cause runaway warming due to the release of most of the enormous boreal carbon stock into the atmosphere due to climate changes (Olsson 2009). Dieback and mortality of trees has already been discussed in previous sections, but if there is a loss of island forests, prairie parkland trees and forest at the southern edge as predicted, large amounts of carbon could be released.

Rate of Decomposition of Soil Organic Matter (SOM)

Geographical patterns of litter decomposition rates and SOM accumulation in major ecosystem types have been related to climate by Meentemeyer and Berg (1986) and Post et al. (1982). Global warming is predicted to cause shifts in the distribution of grasslands, northern coniferous forests and arable lands (discussed previously). This could result in changes between the balance in plant production, decomposition, and net mineralization of carbon pools in litter and SOM in northern temperate and boreal systems (Anderson 1991). The carbon pool for boreal forest SOM is ~182 kg m^{-2}, whereas the biomass portion is only ~84 kg m^{-2}(Anderson 1991). The predicted increases in air temperature from global warming should cause a gradual increase in soil temperature and this should increase the rate of decomposition of dead and dissolved organic matter in the ground and mineral soil layers and reduce the amounts of carbon stored therein (Anderson 1991). The temperature sensitivity of litter decomposition will influence the rates of ecosystem carbon sequestration in a warmer world (Fierer et al. 2005). Bonan and Van Cleve (1992) modeled decomposition in boreal forests under a warming of 5°C for a 25 year period and found that there would be a net decrease (6-20%) in the total ground layer carbon, depending on forest type. Anderson (1991) found in their modeling study that the rate of carbon loss was higher over the next 50 to 100 years in the ground layer than the rates of carbon gain in living biomass. They predicted a 0.3-0.8 Pg/yr loss of carbon stored in boreal forests.

Rate of frozen soil formation

Permafrost is soil at or below the freezing point of water for two or more years(Muller 1945), with regional distributions correlated to mean annual air temperature (Brown 1960). The location of permafrost at its southern limit is a dynamic process that depends on biotic, climatic, and edaphic parameters (Vitt et al. 2000). The distribution of permafrost is continuous in the north and discontinuous in the south, where it can vary from widespread distribution with isolated patches of unfrozen ground to predominantly thawed ground with patches that remain frozen (Brown 1960). Permafrost is important in terms of climate change because it is composed of carbon rich material that worldwide is estimated to store 1672 billion metric tons of carbon (Schuur et al. 2008). The thawing of permafrost represents an incredibly large source of carbon that could be released under warming temperatures due to climate change. It represents one of the most significant potential feedbacks from terrestrial ecosystems to the atmosphere (Schuur et al. 2008). Barry (1984) predicted that a 2°C rise in mean surface temperatures could cause a 200-300 km displacement of the southern boundary of permafrost, while a 3°C warming could lead to >25% reduction of permafrost in Canada. Risk assessments, based on expert judgment, estimated that up to 100 Pg C could be released from thawing permafrost by 2100 (Gruber et al. 2004). The southern boreal forest fringe, including the boreal transition and aspen parkland, has little to no permafrost. Within the mid-boreal lowland permafrost occurs in isolated patches in peatlands, while the mid-boreal upland permafrost is very rare and found only in peatlands. Therefore, in terms of vulnerability, there is little to no risk of permafrost melt causing increasing carbon emission from the southern edge boreal forest along the Prairie Provinces.

Frequency and severity of fires

Fire is a strong influence on the carbon cycling and storage in boreal forests. If global warming increases the frequency and intensity of fires in the southern boreal forest, carbon stocks will be severely affected. Fire has the ability to affect carbon storage in boreal forest in a variety of ways. It can directly release carbon into the atmosphere through combustion of biomass, convert plan material into charcoal (inert form of C), influence secondary succession, effect the thermal regime of soil layers changing decomposition, influence stand age which affect total amounts of carbon stored in forests, and increase soil nutrients for plant growth (Kasischke et al. 1995). Kasischke et al. (1995) modeled these effects on carbon stocks if boreal fire increased under future conditions. If fire was to increase on the landscape by 50%, there would be a net loss of carbon in boreal forests between 2.3 – 4.4 kg m^{-2} and 27.1 – 51.9 Pg C on a global scale. Balshi et al. (2009a) also modeled fire across the boreal forest using a process-based Terrestrial Ecosystem Model (TEM) under the CGCM2 using the A2 and B2 emission scenarios. This study examined the effects of climate change on carbon sequestration, both including and excluding CO_2 fertilization on photosynthesis. They found that relative to the 20th century, total carbon emissions from fire increased by 2.5- 4.4 times by 2091-2100, depending on scenario. However, their simulations indicated that if CO_2 fertilization occurred in the future the North American boreal forest would actually become a carbon sink over the 21st century.

Insect outbreaks are also very important impacts to consider on the forests of western North America as they can have an enormous effect on the carbon storage of forests. During insect outbreaks, the resulting widespread tree mortality reduces forest carbon uptake and increases future emissions of GHG's from the decay of killed trees (Kurz et al. 2008a). Due to the difficulty of predicting the area and severity of insect outbreaks, most modeling studies fail to add this important impact into their analysis of future impacts. However, it is important to being representing this important mechanism by which climate change may undermine the ability of northern forests to take up and store carbon. An example of the magnitude of insect outbreaks on carbon storage can be demonstrated by the mountain pine beetle outbreak in British Columbia where Kurz et al. (2008a) has estimated that the affected region during 2000-2020 will be a source of 270 Mt carbon, turning this forest from a sink to a source of carbon.

Risk Assessment

In the Deloite and Touche framework, risk assessment follows sequentially after the vulnerability assessment, and helps an organization determine how climate change (or other internal and external factors) could affect the ability to achieve outcomes (Sustainable Resource Development 2010; see Table 8). The field of risk analysis has arisen over the last few decades as a useful means to structure and evaluate complex public policy decisions concerning human health and safety (Shlyakhter et al. 1995). Risk analysis is where the consequences of climate change impacts and their likelihood are analyzed. The utility of this step is in assisting decision-makers in focusing adaptation investments and priorities. The risk analysis is a qualitative exercise based on best available professional knowledge, and considers the likelihood and consequences associated with impacts (Sustainable Resource Development 2010). The risks of climate change for a given exposure unit can be defined by criteria that link climate impacts to potential outcomes (IPCC 2007). Integrated risk analyses of global climate change seek to arrive at answers to the following question: What are the likely impacts of global warming upon the world, and can the possible adverse impacts be eliminated or reduced? (Shlyakhter et al. 1995).

Risk can be broken down in the following two components:

1. The **severity** of the impact if it occurred
2. The **probability** of an impact occurring

The severity of the impact will often depend on the social vulnerability of the exposed system and the willingness and ability to adapt to the hazard. Whereas, the probability of predicting a future climate change impact is difficult because all future predictions are surrounded by uncertainty, which is based on an estimate. Uncertainty about the impact of climate change is known to be large because climate change itself is rather uncertain in its magnitude and regional patterns (Bernier and Schoene 2009). Much of our predictions about the future of climate change are based on modeling results and it is well accepted dictum among scientists that "all models are wrong"; however some models can be extremely useful. The process and discussion of the range of possibilities given by models can be used to determine the possibility of future events and potential adaptation options that could be useful under all scenarios. Climate scientists have learned to communicate climate uncertainties quantitatively, now forest managers and policy-makers must learn to integrate theses probabilities systematically into planning and decisions on the ground (Bernier and Schoene 2009). Alberta Sustainable Resource

Development has done a preliminary risk assessment for the impact of climate change on Alberta's boreal forest (Table 7). Their framework has identified five categories that should help the user assess their risk to climate change, these categories are as follows: Strategic, Financial, Operational, Public Perception, and Likelihood. The subsequent sections will try to address these following sections in terms of current climate change studies that may influence these categories.

Strategic

Forestry managers are now starting to incorporate climate change initiatives into their strategic forest management plans. Many government agencies have also started including climate change into their strategic planning for forestry management objectives, for example the USDA forest service has announced the need to include flexible natural resource management and adaptation strategies to help mitigate the effects of climate change and ensure the continued provision of goods, services, and values from forests and rangelands in its 2007-2012 strategic plan (USDA 2007). Many forestry companies in Canada are now including climate change in their forest management plans or admit the need to begin attempting to manage forests in light of predicted climate change events (example: Abitibi Consolidated 2004). In the Whisky Jack Forest FMA, located in Ontario, the local citizen's advisory committee states that "the forest renewal, tending and protection treatments should adapt to climate change affects on the forest. The planning process should include the effects of climate change" (Abitibi Consolidated 2004). Climate change impacts and adaptation options have been incorporated into forest management plans by Mistik Management in NW Saskatchewan, Louisiana-Pacific in SW Manitoba, and Millar-Western in north-central Alberta.

Sustainable Forest Management (SFM): *involves meeting society's need for forest products and other benefits, while respecting the values of people attached to forests and preserving forest health and diversity (Natural Resources Canada 2011)*

Studies have shown the important influence that management strategies may have on forest growth and other goods and services (Blokland 2003; Linder 2000; MOTIVE Project 2011). Linder (2000) used a process-oriented forest gap model to compare forest management strategies with and without climate change. This study found that management strategies (such as length of rotation period, thinning, and species used for regeneration) are important and largely determine the future characteristics of the forest. Additional work is currently being done in Europe on the MOTIVE (MOdels for adapTIVE forest management) project which is investigating adaptive management strategies that address climate and land use change across a broad range of forest types. They have given specific attention to addressing uncertainties and risks for improved decision support tools in forest management.

In Canada, the main theme within our national strategic plan is the call for the use of **Sustainable Forest Management** (SFM). SFM is represented by the Canadian Criteria and Indicators (C&I) Framework created by the Canadian Council of Forest Ministers (CCFM). It is a science-based approach used to define and measure Canada's progress in sustainable forest management and represents forest values that Canadians want to enhance or maintain. This framework was first released in 1995, and adopted by the CCFM in 2003. It provides an efficient way to adapt forestry practices to climate change while maintaining the biodiversity and functioning of the forest ecosystem (CCFM 2006). The use of this framework can help reduce future risk of climate change if the standards are followed and SFM is achieved, because a sustainable forest is a resilient one.

Financial

The economical cost of climate change on forests is difficult to calculate due to future uncertainty, valuation methods, and the difficulty arising in accounting for environmental services. However, financial estimates of the impact of climate change are crucial for deciding on a proper course to take with regards to adaptation or mitigation strategies (Tol 2002). A number of reports have attempted to estimate the price of proactive management of climate change globally, and the cost numbers in the trillions. Reports from the World Energy Outlook estimate that keeping the planet cool and stabilizing the amount of CO_2 at 450 ppm, will cost $542 billion US per year, every year till 2030. The EU estimates that is will be about half that cost (Macleans 2009). Other estimates that focus on forest ecosystems estimate that the net present value of services we gain from forests that is lost each year is between 1.35 trillion and 3.1 trillion dollars (TEEB 2009). Only one study (Perez-Garcia et al. 1997) has looked at the impact of climate change on commercial forestry and included the effect of international trade, forest growth (using the TEM model) and a detailed model of the timber market (CINTRAFOR). Results from this study show that the impact of a 1°C increase in the global mean temperature and the effect of CO_2 fertilization on commercial forestry in America are equal to an increase of ~218 million U.S dollars (Tol 2002). The costs estimated by SRD to deal with key project climate change impacts in the forests of Alberta range from $250 thousand to more than $1.5 million dollars (Table 7).

No exact calculations could be found estimating the cost of climate change on the southern boreal forest fringe in Western Canada. However, the cost of tackling climate change will not be cheap. The economic costs of forest specific impacts such as forest herbivores and pathogens are difficult to reduce to a single estimate because very little information is available for economically important species (Ayres and Lombardero 2000). Some estimates of timber and pulpwood lost to beetles, gypsy moth and pathogens was estimated from thousands to millions of dollars a year (see Ayres and Lombardero 2000). In 2003, BC and Alberta wildfires cost approximately $700 million and resulted in 3 deaths (Lemmen et al. 2008). Climate change also has the ability to affect local revenues from tourism and recreational services when vast areas of dead or dying forests reduce scenic appeal or when sparse snow over reduces skiing season (Bernier and Schoene 2009). This type of risk could be especially important for the island forest and boreal fringe regions of the Prairie Provinces which are near larger urban communities and frequently used for tourism.

Operational

Many forestry operations may be impacted by climate change, including changes in fire prevention protocol, loss of winter harvest time due to decreasing frozen ground, different regeneration strategies, shortening or lengthening rotational periods, timing of harvesting and road building. Changes in these events will have to be taken into account by forest industries and government agencies as climate change continues, and it may be wise for plans to be implemented in advance should theses problems being to occur. Short-term climate events can affect forest operations and access to harvestable wood supplies (Lemmen et al. 2008). Impacts can include flooding, leading to the loss of roads, bridges, and culverts; higher winter temperatures which affect the duration of frozen ground for winter operations, including the ability to construct and maintain ice roads; and water logged soils in cut blocks which prevent equipment operations (Archibald et al. 1997; Lemmen et al. 2008). In wet areas or periods of high precipitation, soils can be deeply rutted by equipment operations, affecting long-term site productivity, ability to regenerate the site and the potential for erosion (Archibald et al. 1997; Grigal 2000; Lemmen et al. 2008). Winter conditions are needed to carry out many forest operations because the frozen soil is relatively impervious to the impact of heavy equipment (Grigal 2000; Lempriere et al. 2008). Therefore, less winter conditions will result in a decrease in the number of harvestable days, potentially reduce harvest, and could significantly increase wood cost (Lempriere et al. 2008). In response to increased winter-kill and insect-caused weakness there will probably be an increase in selective logging, thinning, and fuel management to reduce forest susceptibility to insects and fire (Lempriere et al. 2008). In areas that succumb to increased drought and forest dieback, harvesting levels may be reduced and practices implemented to reduce water stress by thinning tress and increasing spacing. Large natural disturbances like the MPB could create vast areas of materials that bed to be salvaged if value is to be derived from dead timber(Lempriere et al. 2008).

On the manufacturing end, pulp and wood products may not be optimal given the changes in the timber supply that are affected in the future. Evidence of this is already occurring in British Columbia by the current problems processing salvage materials (Spittlehouse 2005). The increase in the use of salvage material has already reduced the average fiber quality.

Public Perception

Public perception is important because decisions wrought by policy makers are influenced not only by scientists, but by the public as well (Leiserowitz 2005). Public risk perceptions are influenced by scientific and technical descriptions, but also by a variety of psychological and social factors, including personal experience, affect and emotion, imagery, trust, values, and worldviews (Slovic 2000). They are critical components of the sociopolitical context within which policymakers operate and can compel or constrain political, economic, and social action to address certain risks. This means that public support plays a strong role in the creation of climate policies (treaties, regulations, taxes, subsides) (Leiserowitz 2005).

Public risk perceptions of climate change are important because Canadians are a strong contributor of green house gases across the globe, producing 16.92 metric tons of CO_2 per capita in 2007. By comparison, India only produced 1.38, Germany 9.57, Japan 9.85, and Russia 10.83 metric tons of CO_2 per capita (IndexMundi 2010). National level surveys in the United States and Canada examined public perceptions on climate change, and found that 80% of Canadians believed the science behind climate change, compared with 58% in the United States. Interestingly, the Prairie Provinces demonstrated the lowest percentages in Canada regarding the belief that global warming has occurred over the last 40 years: 66%, 68%, and 66% of people in Alberta, Saskatchewan, and Manitoba, respectively (Borick et al. 2011). Perceptions of risk are both psychological and social constructs and are formed as a result of personal experience and by learning processes. They are important to take into account because they can help predict behavioral intentions and show the direction Canadians would like to see governmental leadership take on the issue in terms of a policy regimes (Borick et al. 2011).

Likelihood of Occurrence

A climate change risk analysis was conducted by Scholze et al. (2006) who used a dynamic global vegetation model with multiple scenarios from 16 different climate models to determine the likelihood of predicted events based on modeling results. Risk was quantified as the number of model runs in which the critical change occurs, as a fraction of the total number of model runs in the group. Results showed that Canada should be considered a high risk forest, and much forest loss can be expected in the future (Scholze et al. 2006). Risk was shown to increase with degree of climate change, for example, widespread increases in runoff north of 50°N latitude are shown with probabilities as high as 50% even for <2°C, rising to >70% for >3°C. Existing forests are eliminated with a high probability in the southern boreal zone in the Western Canadian Interior, with risks for loss >40% for >3°C (Scholze et al. 2006). Shifts in forests transitioning to non-forest biomes (i.e: grasslands) are >43% for <2°C and increasing to 75% and 88% for 2-3°C, respectively (Table 7). Risks continue to increase beyond the 21st century; however uncertainty also increases with time.

Table 9: Percentage of scenario runs showing a shift from forest to non-forest vegetation (adapted from Scholze et al. 2006).

	Boreal northern latitudes		
Global warming range	5%	10%	20%
T > 3°C	100	88	31
2°C <T <3°C	100	70	10
T < 2°C	75	44	0

Values are the percentages of scenario runs representing a shift from forest to non-forest vegetation (or vice versa) affecting a minimum area specified by the given percentage values (%, 10, and 20%) of the total non-cultivated land area for the boreal northern latitudes

Table 10: Risk assessment for the southern boreal forest under key projected climate change impacts and their affects on forest management and ecosystem services.

Ecosystem services	Key projected Climate Change Impacts	**Risk analysis**							
		Vul. Assessment (H/M/L)	Severity of Consequence: Strategic	Financial	Operational	Protection	Public Perception	Likelihood of Occurrence	Risk Classification (H/M/L)
Water regulations	Drought	High	Multiple changes to strategic direction	Reasonable	Moderate impact on execution of plans	Lost time injury or illness. Moderate environmental impact with limited long-term quality effects	Substantive impact on public.	Very high probability this risk will occur	High
Habitats and Landscape	Shifts in forest ecosystem types	Medium	Multiple changes to strategic direction	Reasonable	Moderate impact on execution of plans	Lost time injury or illness. Moderate environmental impact with limited long-term quality effects	Moderate impact on public image.	50/50 chance this risk will occur	Medium
	Habitat loss and increased fragmentation	Medium	Substantive revision to strategy required	Reasonable	Substantive impact on execution of plans	Lost time injury or illness. Moderate environmental impact with limited long-term quality effects	Moderate impact on public image.	50/50 chance this risk will occur	High
	Loss of forest ecosystems/habitat (forest to grassland climate shift)	High	Multiple changes to strategic direction	Reasonable	Minor impact on execution of plans	Lost time injury or illness. Moderate environmental impact with limited long-term quality effects	Moderate impact on public image.	50/50 chance this risk will occur	Medium
Pest Regulation	Increasing invasive species and biotic forest health damaging agents	High	Multiple changes to strategic direction	Severe	Critical implications for execution of plans	Permanent damage caused by injury or illness. Impact to environmental quality exceeded 25 years to restore	Severe impact to public image. Extended national coverage and/or international media coverage.	Very high probability this risk will occur	High
Genetic Resources	Los of species	Medium	Multiple changes to strategic direction	Reasonable	Moderate impact on execution of plans	Lost time injury or illness. Moderate environmental impact with limited long-term quality effects	Moderate impact on public image.	50/50 chance this risk will occur	Medium

	Loss of within-species forest genetic resources	Medium	Minor changes to strategic direction	Reasonable	Minor impact on execution of plans	Lost time injury or illness. Moderate environmental impact with limited long-term quality effects	Moderate impact on public image.	More likely than not that this risk will occur.	Medium
Carbon Storage	Soil moisture declining below bioproductive levels	Medium	Minor changes to strategic direction	Minor	Moderate impact on execution of plans	Minor injury or illness. Minor impact to environmental quality, easily rectified.	Moderate impact on public image.	50/50 chance this risk will occur	Low
Timber	Increasing frequency and extent of forest fires	High	Substantive revision to strategy required	Major	Substantive impact on execution of plans	Permanent damage caused by injury or illness. Impact to environmental quality exceeded 25 years to restore	Moderate impact on public image.	More likely than not that this risk will occur.	High
	Increase in severity and extent of many forest health damaging agents	High	Substantive revision to strategy required	Major	Substantive impact on execution of plans	Permanent damage caused by injury or illness. Impact to environmental quality exceeded 25 years to restore	Substantive impact on public.	Very high probability this risk will occur	High
	Regeneration failure and reduced tree growth/survival due to drought and severe weather events	High	Substantive revision to strategy required	Reasonable	Moderate impact on execution of plans	Lost time injury or illness. Moderate environmental impact with limited long-term quality effects	Moderate impact on public image.	More likely than not that this risk will occur.	High
	Loss of timber due to increased fire and forest health damaging agents	High	Substantive revision to strategy required	Major	Moderate impact on execution of plans	Minor injury or illness. Minor impact to environmental quality, easily rectified.	Moderate impact on public image.	More likely than not that this risk will occur.	High

Adaptation Options

Adaptation to climate change is any activity that reduces the negative impacts of climate change and takes advantage of new opportunities that may be presented. It refers mainly to local activities that are taken to minimize the harmful effects of climate change (Hogg and Bernier 2005). Adaptation includes activities that are taken before impacts are observed (anticipatory) and after impacts have been felt (reactive). In most cases, anticipatory planned adaptations will incur lower long term costs and be more effective than reactive adaptations (Lemmen et al. 2008). The IPCC defines adaption as " an adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects which moderates harm or exploits beneficial opportunities (IPCC 2007a). Successful use of adaptation does not mean that harmful effects will not occur; only that they will be less severe than would be experienced had no adaptation occurred. Therefore, adaptive actions reduce the risks (decrease vulnerability) by preparing for adverse effects and capitalizing on the benefits (Spittlehouse 2005).

Adaptation is not something to be applied only the future, actions need to be taken now in anticipation of future conditions. Anticipatory adaptation should be taken into account during the planning process, especially when rotation periods are long, as species selected for planting today must be able to withstand and thrive under future conditions (Hebda 1998; Spittlehouse 2001). Sustainable forest management (SFM) embodies many of the activities that will be required to respond to the effects of climate change in forests. SFM’s main objectives focus on maintaining forest health and biodiversity which are important adaptation mechanism in themselves. It is a continuously evolving concept designed to ensure that forests continue to provide a range of ecosystem services (IUFRO 2009). Forest management actions taken to adapt to climate change can be consistent with SFM. For example, healthy forest stands have been shown to exhibit a stronger and faster recovery from disturbances (Hogg et al. 2002a), while the conservation of biodiversity and forest integrity would aid in successful species migrations (Malcolm and Pitelka 2000). These objectives can provide forestry managers with a basic framework into which climate change adaptations can be effectively evaluated and incorporated into forest management decisions. This allows adaptation options for climate change to be developed that fit within existing forest land use planning systems, rather than being viewed as a new and separate issue (Natural Resources Canada 2007a). Although forest ecosystems will adapt autonomously to climate change, their importance to society means that we will want to influence the direction and timing of this adaptation at some locations (Spittlehouse 2005) to ensure the continued supply of goods and services we require from the forest**.** Adaptation options in response to impacts on the timber supply in Canada for the next 50-100 years are limited mainly to forest protection and wood utilization because these forests are already on the landscape. It is important to realize that humans will only be able to assist the adaptation of the forest in Canada on a very small part of the land base. In much of Canada there is a large area of forested land that is not subject to harvesting or reforestation. Consequently, adaption will have to focus on major commercial trees species in reforestation areas, and the rest will have to adapt as best as they can (Spittlehouse 2005)**.** Society will have to accept how the forest naturally adapts, as very little of the landscape will be able to be influenced by human intervention. The southern boreal transition zone along the Prairie Provinces will likely be a prime candidate for adaptation options as the majority of forestry operations occur in the southern boreal forest, and climate change is expected to be especially harmful to this marginal climate. In the Boreal Transition zone, forests may prove to be an ecologically and economically viable alternative to marginally productive agriculture. Therefore, new forest cover in this area could be considered by forestry managers through either natural forest succession or planting of commercial tree species (Natural Resources Canada 2001). Adaptation strategies could begin with assessing forest vulnerability to climate change, revising expectations of forest use, determine research and education needs, development of forest policies to facilitate adaptation and determine when to implement responses (Spittlehouse 2005).

The largest obstacle to tackle when dealing with adaptation for climate change is uncertainty. Uncertainty creates many challenges to adaptation in terms of the magnitude and timing of future climate change events, future market changes, and uncertainty in the future socio-economic context (Spittlehouse 2005). There is uncertainty about how the climate will change, especially at the local and regional level, which is compounded when one considered the impacts of climate change on the forest and the forests potential future state, the degree to which the forest is vulnerable to climate change, and whether management objectives are appropriate or even feasible (Lempriere et al. 2008). Uncertainty is inherent in any plan for the future, but for the most part, forest management decision makers traditionally have assumed that current conditions will continue indefinitely, and they do not take climatic or ecological uncertainty into account to any significant extent (Lempriere et al. 2008). The premise of an uncertain future is best addressed with approaches that embrace strategic flexibility, characterized by risk-taking, capacity to reassess conditions frequently, and willingness to change course as conditions change (Hobbs et al., 2006). It is important to continue to learn from experiences and iteratively incorporate these lessons into future plans, this is adaptive management in its broadest sense, and is the lens through which natural resource management must be conducted (Millar et al. 2007; Spittlehouse and Stewart 2003). It is also important to realize that under uncertain futures, there is no single approach that will fit all situations.

Adaptive capacity is also important to consider when discussing adaptation options. Adaptive capacity is the ability of human social systems such as institutions, systems and individuals to adjust to potential damage, to take advantage of opportunities, or to cope the consequences of climate change. In an organization, adaptive capacity consists of the socio-economic factors determining the capability to implement planned adaption (Linder et al., 2010). Adaptation cannot occur if the system does not have to capacity to implement the required changes options. According to the IPCC, the capacity to adapt to climate change is determine by:

1. Awareness of the issue and perception of urgency
2. Range of technological options available to decision makers
3. Economic resources
4. Institutional factors (design and structure, flexibility, efficiency of resource allocation)
5. Human and social capital of adaptors (skills, education, experience, networks)
6. Knowledge and access to information
7. Ability to manage risk (Smit and Pilifosova 2001)

Forest managers are acutely aware of exposures to climate change, and of the sensitivity of forest to current climate, the question among managers is not whether climate change is real, but what local impacts will be and what adaptation actions should be taken (Johnston et al. 2010b). However, information needed to make these decisions is often lacking at the local scale and fairly sophisticated expertise is often needed to downscaling climate data and performing ecosystem modeling for the area of interest. Other constraints on adaptive capacity includes the availability of economic resources, especially financial resources, in the Canadian forest sector (Johnston et al. 2010b). The forest industry is currently experiencing an economic downturn and most forest managers in industry are focused on day-to-day survival and therefore do not have the time or money to consider climate change and adaption, even in cases where they know this will be important in the future (Johnston et al. 2010b).

Key needs associated with adaptation in the forest sector include: awareness building and debate, improved knowledge and information, vulnerability assessments, planning frameworks and tools, and enhanced coordination, cooperation, and support among governments and other forest sector parties (Lempriere et al. 2008). Successful adaptation will also depend on increased communication of knowledge across disciplines and across land jurisdictions, to develop integrated monitoring systems necessary to detect large scale changes in our forests, especially in drought prone areas in the western portions of Canada (Hogg et al. 2006) where climate change is thought to be more imminent. Meeting the challenges of adaptation will require a sustained group effort for many years to come. Some early efforts to implement adaptation actions have already occurred; some forestry companies have tried incorporating climate change considerations into their Forest Management Plans (Johnston and Williamson 2007). Forest management plans represent a great vehicle for implementing adaption options to combat climate change impacts. Most jurisdictions in Canada require some type of forest management plan, and these usually have a relatively long time horizon and a generally strategic focus which represents a perfect setting in which to establish plans for adopting adaptation (Johnston et al. 2010b). This creates a perfect example of “mainstreaming” climate change adaptation as recommended by the recent Canadian National Climate Change Assessment (Lemmen et al. 2008). Reports show that any adaptive action taken in light of climate change alone is extremely unlikely. Only when climate change adaption initiatives are integrated with other programs, will they be successful in enhancing adaptive capacity(Smit and Wandel 2006).

Currently, provincial and territorial governments are taking actions by developing strategies to address climate change, supporting research into climate change and making efforts to increase awareness of the need for adaptation (Lempriere et al. 2008). In 2007, the Canadian Council of Forest Ministers (CCFM) identified adaptation to climate change as an emerging strategic issue for the forestry sector. The CCFM went on to establish the Climate Change Task Force which has overseen the creation of a number of overview documents on climate change and is now working on facilitation of adaptation initiatives into the forestry sector. A number of documents are currently in the works, such as a framework for assessing vulnerability and mainstreaming adaptation into forestry decision making, a complementary guidebook, a number of reports, guidance documents and case studies across Canada that are looking to showcase adaptation initiatives. SRD has already created a framework for addressing risk and vulnerability to climate change (Alberta’s Climate Change Adaptation Framework). This framework uses a capabilities approach to identify adaptation options and the basis of this method focuses on four critical areas that organizations should consider when developing a list of potential adaptation options (Sustainable Resource Development 2010). These areas are People, Process, Technology, and Governance. The following definitions for each of the four categories have been taken from Alberta's Climate Change Adaptation Framework Manual (Sustainable Resource Development 2010):

- **People** – Adaptation options that improve the ability of the individuals with an organization, and external stakeholder for managing risk. Examples include: training, recruitment and retention strategies, updated job descriptions and performance management
- **Process** – How work is accomplished within an organization. Processes for climate change adaptation include: develop and deploy strategies, identify and assess risks, response to risks, design and test measures, monitor and re-evaluate progress and sustain and continuously improve. Cooperation between business units and departments is critical.
- **Technology** – application of science to adapt to environment. This could include a variety of high and low tech options available for assessing and addressing climate change risks. Specific examples include climate modeling software, GIS, field equipment, monitoring equipment and infrastructure
- **Governance** – management, policies and processes to direct the activities of the organization. This could include policy, resource decisions, and facilitation of cross organization relationships. Specific examples include: licensing and approvals on surface land, compliance strategies, quotas or regulatory limits on disturbance or access, etc.

The following section will be a collection of tables which shows the relevant ecosystem services for the Southern Boreal Forest Fringe and associated adaptation options that could be found in literature. Each adaptation option will be broken down into the four critical areas that should be considered when assessing whether to implement an adaptation option. Keep in mind that the majority of these options are very general in context and many have yet to be tested. They are included in this document to give the breadth of current thinking around adaptation options available to forestry managers, but also to help guide initial thinking. Most of these options will need to be narrowed down and focused on the area of interest.

	Adaptation options	References
People	Increased communication of knowledge across disciplines and across land jurisdictions	(Hogg et al. 2006)
	Educate policy/decision makers and the public to increase awareness of drought risks to forest and create acceptance of new adaptation strategies and policies such as intensive forest management and use of drought-hardy non-native species.	SRD
	Migrate away from areas prone to serious drought effects	(IUFRO 2009)
Process	Reforestation with drought-tolerant provenances from more southerly or low-elevations	(Papadopol 2000) (Spittlehouse and Stewart 2003)
	Replace current drought sensitive species in areas prone to drought stress	(Cerezke 2009)
	Precommercial thinning of stands to conserve soil moisture	(Papadopol 2000) (Spittlehouse and Stewart 2003)
	Planting larger stock	(Man and Lieffers 1999)
	Scheduling reforestation activities for the wettest periods	(Man and Lieffers 1999)
	Applying alternative measures such as partial cutting to ameliorate seedling microclimate	(Man and Lieffers 1999)
	Introducing exotic trees more suited to drier, warmer conditions	(Henderson et al. 2002)
	Human-assisted migration of drought tolerant trees through artificial regeneration. Especially in places where the climate becomes too try for the existing tree species to survive	(Hogg and Bernier 2005)
	Collect seeds from dry microsites in and outside the area of interest (e.g.: island forests) and create	(Bendzsak 2006)

	plantation trials. This could serve as analogues for future moisture conditions	
	Replacement of tree species with substitutes that are more tolerant of forcasted climatic conditions (e.g: Maintain pine ecosystem in Cypress Hills by planting Ponderosa pine (instead of lodgepole)	(Bendzsak 2006)
Technology	Develop the integrated monitoring systems that are necessary to detect large-scale changes in our forests, especially in the drought-prone areas in the western portions of Canada	(Hogg et al. 2006)
	Development and use of techniques that can rapidly and efficiently identify drought tolerant tree species/provenances/genotypes.	SRD
	Improve drought hardiness through genetic manipulation	(Aguado-Santacruz 2006)
	Perform transcript profiling and identify gene expression in response to water deficit to discover different varieties of drought tolerance	(Jain and Chattopadhyay 2010)
Governance	Requires amending of *Standards for Tree Improvement in Alberta,* strata balancing policies, and regulations regarding planting of non-native trees on crown lands	SRD
	Address policies that do not allow the plantation of exotic species	(Thorpe et al. 2006)

Photo obtained from: http://en.wikipedia.org/wiki/File:Drought.jpg

	Adaptation options	References
People	Work with others to ensure that stressors outside the control of forest managers (e.g., atmospheric pollution) are minimized	(Ogden and Innes 2007)
Process	Explore opportunities for assisted migration of populations and species.	SRD
	Explore potential exotic species that may be compatible with new climates and existing ecosystems.	SRD
	Difficult to prevent without dealing with climate itself. Can delay transition through improved disturbance management to maintain existing forests subjected to a grassland climate.	SRD
	Explore intensive forest management and potential exotic tree species that may be compatible with new climates.	SRD
	Mitigate habitat loss by habitat enhancement strategies	SRD
	Reduce human-caused habitat loss/fragmentation	SRD
	Explore opportunities for assisted migration to enable populations and species to track their shifting optimal climate.	SRD
	Explore potential exotic species that may be compatible with new climates and existing ecosystems.	SRD
	Manage for asynchrony and use establishment phase to reset succession. This can be achieved by promoting diverse age classes, species mixes, within-stand and across landscape structural diversities and genetic diversity	(Millar et al. 2007)
	Use regeneration to increase tree species diversity and create mixed stands	(Keskitalo 2011)

	Maintenance of forest edges	
	Use practices that spread risk rather than concentrate them	(Millar et al. 2007)
	Experiment with refugia populations. They may be more buffered against climate change and short term disturbances and could be considered for long-term retention of plants or for establishment of new forests	(Huntley and Webb 1998)
	Reduce non climatic stresses to enhance ability of ecosystems to respond to climate change by managing tourism, recreation and grazing impacts	(Biringer 2003) (Ogden and Innes 2007)
	Reduce non climatic stresses to enhance ability of ecosystems to respond to climate change by regulating atmospheric pollutants	(Biringer 2003) (Ogden and Innes 2007)
	Reduce non climatic stresses to enhance ability of ecosystems to respond to climate change by restoring degraded areas to maintain genetic diversity and promote ecosystem health	(Biringer 2003) (Ogden and Innes 2007)
	Promote connected landscapes with few physical or biotic impediments to migration through which species can move readily	(Halpin 1997)
	Maximize forest area by quickly regenerating any degraded areas	(Biringer 2003) (Wheaton 2001)
	Practice low intensity forestry and prevent conversion to plantation	(Noss 2001)
	Thinning stand to reduce competition	(Fussel and Klein 2006)
	Help establish neo-native forests by researching information from historical ranges and responses to climate.	(Millar et al. 2007)
Technology	On the ground monitoring of native species can provide insight into what organisms are experiencing, and indicate the directions of change and appropriate response at local scales	(Millar et al. 2007)
	Re-examine replicated forest plantations such as old genetic provenance or progeny tests as a means of gathering information about adaptation to recent and ongoing changes	(Millar et al. 2007)

	Surplus seed banking	(Ledig and Kitzmiller 1992)
	Perform testing and screen new species to examine associated risk and benefits of planting exotics	(Bendzsak 2006) (Thorpe et al. 2006)
	Adopt a holistic management approach that balances timber and non-timber goods and services	(Ogden and Innes 2007)
Governance	Modification of regulations prohibiting planting of exotic species.	SRD
	Modification of Standards for Tree Improvement in Alberta to increase flexibility in planting outside of existing seed zones.	SRD
	Modification of regulations prohibiting intensive forest management and planting of exotic species.	SRD
	Modification of seed transfer regulations in Alberta to increase flexibility in planting outside of existing seed zones.	SRD
	Modification of regulations prohibiting planting of exotic species.	SRD
	Address any institutional and policy barriers to reforestation standards	(Spittlehouse 2005)

	Adaptation options	References
People	Increased public education about invasive species	SRD
	Implement public programs on invasive species and a number to call if the species is spotted	
Process	Prevent invaders from becoming permanently established by controlling when population is small	SRD
	Use of alternative/enhanced forest management strategies	SRD
	Adjust harvest schedules to harvest stands most vulnerable to insect outbreaks	(Lemmen et al. 2004) (Ogden and Innes 2007)
	Plant genotypes that are tolerant of drought, insects and disease	(Farnum 1992) (Namkoong 1984) (Kellomaki et al. 2005)
	Reduce disease losses through sanitation cuts that remove infected trees	(Smith et al. 1997)
	Breed for pest resistance and for a wider tolerance to a range of climate stresses and extremes in specific genotypes	(Namkoong 1984) (Wang et al. 1995) (Kellomaki et al. 2005)
	Use prescribed burning to reduce fire risk and reduce forest vulnerability to insect outbreaks	(Lemmen et al. 2004)
	Employ silvicultural techniques to promote forest productivity and increase stand vigor (e.g partial cutting or thinning) to lower the susceptibility to insect attack	(Biringer 2003) (Dale et al. 2001) (Gottschalk 1995)

	Controlling catastrophic insect or vegetation disturbances by biological, chemical or physical controls	(Wargo and Harrington 1991) (Henderson et al. 2002) (Cerezke 2009)
	Take early defensive actions at key migration points to remove or block invasions as a key resistance point	(Millar et al. 2007)
	Shorten the rotation length to decrease the period of stand vulnerability to damaging insects and diseases and to facilitate change to more suitable species	(Linder 2000)
Technology	Increased investment in monitoring equipment for invasive species and pests to allow implementation of the strategy of early detection and rapid response (EDRR)	SRD
	Creation of novel pheromone applications to attract insects	(Millar et al. 2007)
	Surveillance technology needs to be deployed to monitor biotic agents for their potential to cause tree and forest damages	(Cerezke 2009)
Governance		

Photo obtained from: http://scienceline.org/2008/05/env-olson-pinebeetle/

Genetic Resources

	Adaptation options	References
People	Develop your organizations perspective on risk and manage accordingly by prioritizing species, provenances, and sites for sensitivity to climate change	(Howe and St. Clair 2009)
	Address negative public perceptions regarding clonal forestry and genetically engineering or modifying commercial tree species for better survivability under climate change	(Howe and St. Clair 2009)
Process	Initiate new populations through facilitated migration as new habitat becomes available. They can be small and consist of founder populations or "islands" which provide a nucleus for range expansion via seed dispersal as climate changes.	(McLachlan et al. 2007)
	Establish 'genetic outposts', which are stand adapted to future climates planted near native forests that help facilitate assisted migration at the pollen level	(Howe and St. Clair 2009)
	Assisted migration by moving species, provenances, or breeding populations where they are expected to be better adapted in the future	(Howe and St. Clair 2009)
	Match genotypes to sites and future climate using current breeding populations; families and clones differ in drought/cold hardiness and growth	(Howe and St. Clair 2009)
	Genetic engineering and marker-aided selection	(Howe and St. Clair 2009)
	Create clonal forests which could speed adaptation to future climates via traditional breeding and deployment of genetically-engineered materials	(Howe and St. Clair 2009)
	Establish new species and varieties that would be best adapted to the range of possible future climates	(Henderson et al. 2010)
	Protect primary forests in forest interiors by maintaining large patches of old growth forests to help maintain biodiversity	(Noss 2001)

	Maintain diverse gene pools within and among populations of commercially important trees and other forest species	(Dudley 1998)
	Perform short-term nursery tests to examine sensitive traits which have the strongest correlations with temperatures. Relative risk can be used to judge the potential of maladaptation. This can provide information on new species cheaply and quickly.	(Howe and St. Clair 2009)
	Perform long-term provenance tests to assess complex climatic regimes over a long time in the field and find traits relevant to production forestry	(Howe and St. Clair 2009)
	Legislated development and implementation of recovery plans for listed species (e.g. whitebark and limber pine)	SRD
	Increased seed collections and planting of commercial species combined with strategic location of in situ reserves	SRD
	Ensure more regionally representative and adequate reforestation seed supply	SRD
Technology	Create provenance and breeding programs to create species adapted to a wider range of climate conditions. This could encompass existing trees and possible new species introductions	(Henderson et al. 2010)
	Gene management, breeding for pest resistance and climate stresses and extremes	(Spittlehouse and Stewart 2003)
	Use models and climate scenarios to determine seed transfer models for reforestation	(Beaulieu and Rainville 2005)
	Use reforestation techniques instead of allowing natural regeneration	(Noss 2001)
	Studies need to be done of population responses to climate change that focus on genetics	(Bawa and Dayanandan 1998)
	Create a forest genetics database	(Howe and St. Clair 2009)
	Create a interactive web-based tool to generate seed zones and zones for future climates for Canada	(Howe and St. Clair 2009)

	Create growth models that incorporate climate change, species, and provenance variation	(Howe and St. Clair 2009)
Governance	Expand genetic diversity guidelines as past guidelines were based on the assumptions that the climate was not changing.	(Ledig and Kitzmiller 1992) (Spittlehouse and Stewart 2003)
	For commercial species, adjust reforestation policies with altered seed transfer rules to maintain species, populations, and genes.	SRD

Photo obtained from: http://www.ait.ac.at/departments/health-environment/business-units/bioresources/?L=1

Adaptation options		References
People	Educate the public on FireSmart Strategies and possible risks of climate change to communities	
	Hold workshops and seminars open to the public to educate them on the risks of climate change and how they can begin to adapt	
Process	Improved management/silviculture	(Keskitalo 2011)
	Decrease rotation length in order to reduce the risk of exposure to hazards such as storms or fires, thus also decreasing costs and increasing potential revenue from production. Follow by planting to speed by establishment of better adapted forest types	(Ogden and Innes 2007) (Lindner et al. 2010) (Kellomaki et al. 2005) (Keskitalo 2011)
	Increased thinning of forest stands; manipulate stand density and species composition	(Keskitalo 2011) (TAFCC 2010)
	Alternatives should be considered to clear-felling systems where suitable sites and species combinations allow, such as selective cutting or small scale cutting	(Keskitalo 2011)
	Afforestation	
	Increased investment in forest protection capacity	SRD
	Acceleration of FireSmart Strategies to protect forest communities	SRD (Spittlehouse and Stewart 2003)
	Implement forest landscape planning to create future forests with reduced fire, insect, and disease susceptibility	SRD
	Implementation of Early Detection and Rapid Response (EDRR) strategies where appropriate	SRD

	Explore potential exotic species that may be suitable in new climates with neutral or negligible negative effects to nearby ecosystems	SRD
	Explore opportunities for assisted migration of highly productive populations and species to new favorable areas created by climate change	SRD
	Explore more intensive commercial forest management on selected parts of the land base	SRD
	Mitigate impact of losses on individual FMAs through creation of larger "timber baskets" that allow wider and more flexible movement of wood	SRD
	Plant genetically modified species and identify more suitable genotypes	(Ogden and Innes 2007) (Gitay et al. 2002) (Kellomaki and Vaisanen 1996) (Lemmen et al. 2004)
	Reduce losses to timber supply through increased investments in forest protection capacity	SRD
	Enhance forest growth through forest fertilization or irrigation	(IPCC 2000) (TAFCC 2010)
	Apply silvicultural rules and practices to ensure the growth rates of trees is maintained or enhanced	(IPCC 2000)
	Practice high intensity forestry in areas managed for timber production to promote growth of commercial tree species and where the forested landbase is allocated using a TRIAD approach to landscape zonation	(Innes and Nitschke 2005) (Ogden and Innes 2007)
	Practice adaptive management which rigorously combines management, research, monitoring, and means of changing practices so that credible information is gained and management activities are modified by experience	(Ogden and Innes 2007) (Spittlehouse and Stewart 2003)
	Reforest immediately after harvest	(Cerezke 2009)
	Implement tree planting programs for regeneration after a fire/loss	(Henderson et al. 2010)
	Retain forest cover on the landscape by maintaining a diversity of age stands and using forest harvest activities to help create more age-stand diversity	(Henderson et al. 2010)
	Use prescribed fire breaks to reduce fuel loads or stimulate regeneration	(Henderson et al. 2010)
	Manage for fire creating and maintain fire breaks where necessary	(Henderson et al. 2010)

Technology	Improve modeling and pest risk assessment capabilities, and ensure when doing so that climate models are synthesized with pest/host dynamics (and perhaps other variable factors such as timber markets)	SRD
	Include climate variables in growth and yield models in order to have more specific prediction on the future development of forests	(Kellomaki et al. 2005) (Ogden and Innes 2007)
Governance	Establish reforestation standards that incorporate Sustainable Forest Management under climate change	SRD
	Increased investment in forest health monitoring and control capacity	SRD
	Increased investment in research to develop enhanced forest management strategies to reduce the impacts of forest health damaging agents	SRD
	Modify seed transfer rules for commercial species, both wild and genetically improved, to maintain productivity and forest health	SRD
	Creation of larger "timber baskets" requires tenure reform and changes to existing Forest Management Agreements	SRD
	Amend seed transfer guidelines to allow greater flexibility in seed movement across seed zone boundaries, and allowing exotic species where native ones fail	(Kellomaki et al. 2005) SRD (Ogden and Innes 2007)
	Remove barriers and develop incentives to adapt to climate change in forest management policies	(Ogden and Innes 2007)
	Provide long term tenures to encourage long term considerations within short term decisions	(Ogden and Innes 2007)
Photo obtained at: http://www.panoramio.com/photo/4566848		

Adaptation options		References
People		
Process	Minimize risk of the forest ecosystem being a net source of carbon	(Ogden and Innes 2007) (IPCC 2000)
	Enhance forest growth and carbon sequestration through forest fertilization	(Ogden and Innes 2007) (IPCC 2000) (Cerezke 2009)
	Modify thinning practices (timing, intensity) and rotation length to increase growth and turnover of carbon	(Ogden and Innes 2007) (Kellomaki et al. 2005)
	Minimize density of permanent road network to maximize forest sinks	(Spittlehouse and Stewart 2003)
	Decommission and rehabilitate roads to maximize forest sinks	(Spittlehouse and Stewart 2003)
	Identify forested areas that can be managed to enhance carbon uptake	(Ogden and Innes 2007) (White and Kurz 2003) (Spittlehouse and Stewart 2003)
	Expand existing forest carbon sinks in areas where “high-grading” has occurred in the past and where carbon storage potential can be increased, for example reforesting marginal agricultural land	(Cerezke 2009)
	Restore the productive forest cover on stands that did not regenerate properly after harvest	(Cerezke 2009)
	Establish new plantations which replace low productivity forest vegetation on fertile soils	(Cerezke 2009)

	Identify areas that have been degraded and can be rehabilitated	(IPCC 2000)
	Reduce forest degradation and avoid deforestation	(IPCC 2000)
	Decrease the impact of natural disturbances on carbon stocks by managing fire and forest pests and by enhancing forest recovery after a disturbance	(IPCC 2000) (BCMOF 2006) (Lemmen et al. 2004) (Wheaton 2001)
	Practice low intensity forestry and prevent conversions to plantations	(Noss 2001)
Technology	Use low impact harvesting activities to reduce the impact on soil disturbance	(IPCC 2000)
Governance	Provide incentives and remove barriers to enhancing carbon sinks and reducing greenhouse gas emissions	(BCMOF 2006) (Ogden and Innes 2007)
	Provide opportunities for forest management activities to be included in carbon trading systems (e.g. as outlined in Article 3.4 of the Kyoto Protocol)	(Ogden and Innes 2007)

Photo obtained from: http://www.tgdaily.com/sustainability-features/50402-carbon-sequestration-could-be-ticking-time-bomb-says-scientist

Conclusions

Forest are important ecosystems for humanity as they provide jobs, recreational and ecosystem services, wildlife habitat, food, fiber, fuel and are of cultural and spiritual importance. The southern edge of the Canadian boreal forest fringe which lies along the Prairie Provinces is especially important as it provides the majority of these services due to its closer proximity to urban centers. Forests in Canada's Prairie Region are likely to be highly vulnerable to the impacts of climate change, particularly along the southern fringe (Johnston and Williamson 2010). These impacts are expected to be pervasive, ongoing, and largely negative. The purpose of this report is to provide a literature review which provides scientific documentation of vulnerabilities, risks, and adaptation options for a number of proposed climate change impacts on the southern boreal forest across the three Prairie Provinces. Vulnerabilities and risks to important ecosystem services provided by this region were established by the Alberta Sustainable Resource Development (SRD) using the Climate Change Adaptation Framework developed by Deloitte and Touche. Potential climate change impacts and adaptation options for the southern boreal fringe and each Prairie Province were given where available; however, many inferences were collected from scientific reviews that cover a more extensive landscape.

Climate is the driving force behind ecosystem functioning and climate change models predict that increases in temperature and decreases in moisture will likely occur over much of the southern boreal forest. Although there is some on the actual magnitude of change, the direction is almost certain. These changes in climate are predicted to be strong enough to cause impacts to many ecosystem services in the forest, including water supply, pest regulation, habitat, timber supply and carbon sequestration. The vulnerability of these services to climate change was identified, quantified and ranked by SRD across the boreal forest. Areas predicted to be **highly vulnerable** to climate change impacts were: drought, loss of forest and timber supply, increase pest damage and forest fires, decreased regeneration and revenue to the forest industry. Areas identified as having **medium vulnerability** to climate change were: shifts in forest ecosystems, habitat loss and fragmentation, loss of species and with-in species genetic resources, and reduced carbon storage.

Extreme drought events are predicted in increase in frequency and intensity in the southern boreal forest. Consequently, decreases are expected in tree growth, regeneration, carbon sequestration and survival, while fire, susceptibility to pest attack and mortality are expected to increase. Drought may be the driving force behind many of the other climate change impacts on forests, acting in consort or as a catalyst for many of the aforementioned vulnerabilities. Drought events have already been noted in areas of the aspen parkland and boreal transition zones, where stands of aspen have succumbed to drought and speculations insist that these are the early warning signs of climate change. Effects of drought are mostly likely to be seen in transition zones, as these regions are already at the margin of their current existence. This makes the island forest of the boreal plain and southern edge of the boreal forest **highly vulnerable** to the effects of drought predicted under climate change and this is in concurrence with SRD's assessment.

Under a changing climatic regime, trees will have three options: adapt, migrate, or become extirpated. Many scientists attest to the fact that adaptation is too slow a process as it occurs over many generations, and most species will become maladapted to their current climate and therefore will need to migrate with changing environmental conditions to continue to survive. Migration rates seem to vary by species of tree and by study; however most studies agree that current migration rates will not be able to keep pace with predicted climatic shifts. This leads many trees left with one option, extirpation. Newer studies now argue that many of these older theories regarding maladaptation and slow migration rates are faulty. They suggest that trees have the genetic resources to quickly adapt to climate change and have done so in the past. The boreal forest as a whole is genetically diverse and therefore a loss of species at the trailing edge of this zone may not have a large impact on the overall genetic diversity of the forest. However, genetic resources are unknown for trees located in remnant and isolated forests, like the island forests scattered across the southern boreal fringe. If the trees in this region have been isolated enough to have established unique genetic characteristics, there is a potential loss of genes if these forest die out. Overall, the risk of loss to genetic diversity within tree species is actually quite **low** according scientific literature and this should be placed at a lower concern unless new information is revealed. This area of research needs more work before concrete assertions can be claimed.

A few points can be assumed, however: habitats and landscapes in the southern boreal forest fringe will be among the first areas to suffer the effects of climate change. This region is likely to become slowly degraded and fragmented over time if climate change occurs as predicted. This may initially lead to changes in dominance of tree species (e.g. conifer to aspen) or changes in species mix. If climatic stressors become overwhelming, trees will suffer higher mortality, reduced regeneration, and disturbances such as fire may permanently remove them from the landscape. Fire is likely to increase with increase temperature and decreasing moisture predicted by climate change models. Fire is a strong agent of change and its effects can be large enough to cause shifts in species type, a decrease in carbon sequestration and extirpation of forest cover if the fire frequency increases above the limit of tree tolerance. Risk and vulnerability to this impact is **very high** because people have a limited ability to prevent fire over the landscape and as fire frequency increases, prevention measures may have to focus on particular areas of interest like wild land – urban interfaces and parks.

Like fire, Insect outbreaks and diseases are predicted to increase as temperatures rise and are also large agents of change in forest ecosystems, affecting more area each year than fire. Distributions of these pests are also expanding northward as temperatures increase and there is concern that new and exotic pests may become established across Canada as warming trends continue. The effects on diseases are largely unknown and more information is needed to make proper predictions. Insects are closely linked with temperature and warmer temperatures will increase insect outbreaks in extent and severity. This leads to the summation that the southern boreal forest is **highly vulnerable** to insect outbreaks in the future.

Due to these multitude change predicted to affect the forest edge, productivity is likely to change under rising GHGs but the direction of this change is still up for debate as many reports are currently ambiguous regarding the effects of CO_2 fertilization and increased WUE in the field. Most studies agree that areas that are restricted by moisture or nutrients will like suffer a decrease in productivity, and consequently lead to increases in fire, insects and disease. Positive effects will likely occur in moister regions of the forest, and they may benefit from CO_2 fertilization, increased growing season and greater productivity. These effects are likely to vary by species and across the landscape of the southern boreal forest. Any positive benefits of climate change such as longer growing season, increased temperatures, CO_2 fertilization, increase WUE, and potential for increase productivity will be counteracted by moisture stress, low nutrient availability, fire, insects and disease. Consequently, productivity and in turn timber supply, will likely be variable across the landscape and forest managers will have to determine which factors will be most pronounced at their sites of interest and take responsive measures.

Information on risk analysis was difficult to obtain for the study region and adaptation options were varied and often untested. Conclusions summarized from the material are quite general in nature, however, a few key points could be extracted. Firstly, it is important for forest managers to begin thinking about climate change risks to their operations and start implementing plans to counteract potential impacts and risks into their Forest Management Plans. Proactive adaptation is better and usually cheaper that reactive adaptation, so the sooner these plans are implemented the better able forest industry will be able to cope with climate change. Sustainable Forest Management (SFM) is a good place to start when attempting to deal with risk. This scientific based approach helps forestry practitioners adapt practices to climate change while maintain proper forest functioning. SFM helps reduces future risk by enhancing forest resiliency to climate change. Financial risk is currently unknown for forestry operations but predicted to be very large. The best option to take is to implement adaptation plans that are win-win options. These types of options contribute to both climate change mitigation and adaptation and wider development objectives, such as business opportunities from energy efficiency increases or sustainable management and would constitute a justifiable change even in the absence of climate change. What is known regarding financial risk is that adaptation measures will be more costly in the future as ecosystems continue to degrade; therefore it is prudent to start adaptation actions now to avoid future financial costs.

Management that aims simply to retain existing vegetation, or to restore historical vegetation distributions and ecosystems, will fail as the climate moves father away from its current condition. Actions will need to be taken to protect the Canadian forest by maintaining a diversity of age classes, responding aggressively to insect and pathogen disturbances, and actively regenerating the forest with existing or alien tree species that are better adapted to new climate parameters (Henderson et al. 2002; Lemmen et al. 2008). Increased fire suppression and augmented forest regeneration efforts could slow or possibly halt the shift to grassland. But the business case of additional industry expenditures is currently weak, given that rising energy and labor costs are threatening the forestry sector’s ability to generate income, e.g. in Alberta (Alberta Forest Products Association 2008). There may come a time when it becomes too expensive for the government to continue suppressing fires (Schneider et al. 2009) or implementing adaptation practices in these unique regions.

The negative impacts of climate change can be reduced through proactive adaptation. Many adaptation options have been provided within this report for consideration. However, these adaptation options are relatively general, and therefore organizations will have to find specific actions plans for their landscapes. Adaptation is a new area of research and many of the examples provided in the literature are based on theories and very few have been put into practice. They will need to be implemented on a case by case basis; the options listed in this report are meant to lend a direction or ideas to get forest managers started in the right direction. Therefore, adaptation is possible via forest management and genetic and silvicultural options are currently available and should be used in an adaptive way that corresponds with individual forest sites. It is important to know the local forest conditions, its current and future stressors and limitations. In terms of the southern boreal forest, the future stressors are multivariable and can often be overwhelming. It is important to start planning for change now, using the information provided here to evaluate management objections, risks and opportunities. Be aware that uncertainty must be accepted and plan to be able to monitor adaptation measures and be willing to quickly change them if necessary. Flexibility, monitoring and accepting uncertainty will be key in beginning to apply adaptation measures in forest landscapes.

Humans have impacted forests even prior to recorded history, and it is likely that future forests will have to sustain impacts at least as great as those of the past. If the human population continues to grow, forests will exist only within the context of societal needs. However, the most basic of those needs is a functioning global ecosystem, which depends largely on the forests. Therefore, it is in our best interests to maintain diversity and promote system redundancy and resilience (Ledig 1992).

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