

**LIMITED REPORT**

**Climate Change Impacts and Adaptation Options  
for the Island Forests of Saskatchewan**

Prepared for

Prairie Regional Adaptation Collaborative (PRAC)

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## Summary

This report contributes to the forestry component of the Prairie Regional Adaptation Collaborative (PRAC) and focuses on developing a vulnerability assessment and targeted adaptation options for a specific area within the boreal forest fringe of Saskatchewan, the Island Forests.

This report examines the effects of climate change on the Island Forests in Saskatchewan using the climate change adaptation framework manual from Alberta's Sustainable Resource Development (Sustainable Resource Development 2010). A vulnerability assessment was done using this manual, followed by modeling some of the established vulnerabilities and determining appropriate adaptation options that could be established to reduce the impacts of climate change on this region. The modeling approach used LANDIS (LANDscape Disturbance and Succession), a forest landscape simulation model which can estimate forest change over large spatial scales and long time frames. LANDIS was used in combination with a forest ecosystem process model, PnET-II, which models carbon and water cycles in forest ecosystems. These two models were used in conjunction to examine climate change impacts such as forest productivity, changing fire regimes, and species distributions, under a single climate model. Once a range of potential vulnerabilities were determined under future climate change scenarios we then recommend adaptation options to reduce the risk and impact of climate change in the Island Forests surrounding Prince Albert, Saskatchewan.

Results from this modeling analysis show that the Island Forests will likely see a decline in forest productivity over the next century based on the CRCM4.2 model under an A2 emissions scenario. Increased temperatures and fire will likely be the main factors contributing to the decrease in forest biomass and aboveground net primary production. Hardwood species, such as aspen and balsam poplar, will be the most viable species under climate change and will supplant many areas currently occupied by softwood species. Jack pine will likely remain on the landscape, however at a much lower dominance level than currently present. Forest managers will need to consider adaptation options that focus on fire suppression or tolerance as well as species that may be more productive under a warmer climate and increased fire.

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## 1. Scope and Preparation:

### Introduction

Forests cover almost one-half of Canada's land mass, an area representing about 10% of the world's forested land. They have a crucial role in this country's environment and strongly influence climate, watersheds, wildlife and fisheries habitats (Curran 1991). Forests are important to Canada's economic health as the forest sector is a major provider of employment and a major source of revenue for governments, both federal and provincial (Curran 1991). Therefore, management of Canada's forest resource, including its protection and regeneration, is essential to the national well-being of the country.

It is now widely acknowledged that increasing greenhouse gases (GHG) such as CO<sub>2</sub>, are the major cause of recent increases in global mean temperatures and changes in the world's hydrologic cycle. Since 1850, the average surface temperature on the Earth's surface has increased by about 0.78°C (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). According to the Intergovernmental Panel on Climate Change (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<sup>st</sup> century is likely to be between 1.1 – 6.4°C, depending on GHG emissions scenarios (IPCC 2007). Evidence suggests that the world may well be facing decades, if not centuries, of warming. At a minimum, the current buildup of GHGs in the atmosphere commits the world to a further 0.6°C of warming over the next three decades (Budikova et al. 2010).

Temperatures in Canada have risen faster than the globe as a whole. During the period of instrumental record (1895 until present day), there was an average increase in temperature of 1.6°C for the Prairies, a rate that is almost twice the global average (Zhang et al. 2000, NRTEE 2010). The largest temperature increases are currently found in the upper latitudes of the Northern Hemisphere, where the boreal forests reside (IPCC 2001b). This warming trend is seen in both daily maximum and minimum temperatures, and has caused widespread reductions in the number of days below freezing during the latter half of the 20<sup>th</sup> century (IPCC 2007). In the last 50 years, more extensive regional warming has been experienced, with significant trends in January, March, April and June (Gan 1998). 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 (Gan 1998, Barrow et al. 2004, Johnston et al. 2010a).

A warmer climate and higher future concentrations of CO<sub>2</sub> in the atmosphere will affect the growth, survival, and reproduction of Canada's forests, perhaps even changing the nature and extent of those forests (Curran 1991). The Island Forests that surround Prince Albert will most likely be one of the first boreal forest areas to respond to climate change due to their southerly location at the edge of the boreal forest (where forests are transitioning to grasslands), and their poor sandy soils, which make them further prone to effects of climate change, especially drought. Many studies report that regions such as this will suffer greatly as climate change occurs, due to their small size, isolation, and location at

the prairie-forest ecotone (Henderson et al. 2002). If this is true, the Island Forests represent the part of the boreal that will require the earliest adaptation and management efforts, and represent a good opportunity to develop best practices for adaptation on a small scale.

The emphasis in this report will be on considering multiple sources of vulnerability and opportunities in a climate change adaptation context that can be useful to forest management plans and modification of forest management policy to effectively cope with climate change. A meeting with provincial government officials helped to establish some preliminary goals to set with regard to this project. Some of the important management questions they identified are as follows:

- 1) How does climate change affect wood supply in the future?
- 2) How do we incorporate climate change into forest management plans?
- 3) Would characteristics of the wood and pulp change under climate change? (we are unable to address this under the current study)
- 4) Are all changes going to be negative? What about positive changes? Will some areas be converted from wetland into forest?
- 5) What tools are available to forest managers to address climate change and adaptation?
- 6) Is it possible to apply future fire scenarios and their impact on future wood production? What are different techniques that can be used to decrease fire susceptibility?

The Island Forests is a good place to start answering many of these questions, and the majority of the proposed questions can be addressed in this study to some extent. This study provides estimates of future net primary production with and without fire, which can be directly related to wood supply. Positive or negative trends can be inferred from modeling results. Adaptation options are presented which can be then be incorporated into management plans. This work will outline the tools that were used to address climate change and adaptation. Wood and pulp characteristics are currently beyond the scope of this study, as the model LANDIS does not take these factors into account. Moreover, the province is interested in the boreal forest across a greater range; therefore, it is important to be able to scale this work up to a larger extent. We have addressed the issue of scale by choosing a model that can be scaled up to a larger region and is known for being able to model millions of hectares of forest land (Gustafson et al. 2010).

## Study Area

The southern edge of the boreal forest across the prairie provinces of Canada is highly vulnerable to climatic extremes and climate change (Lemmen et al. 2008). Scattered across this boundary are island forests, refugia of trees and tree-dependent species isolated in a sea of grasslands and agriculture (Figure 1) (Henderson et al. 2002). These unique and valuable forests occur on sandy deposits formed near the end of the last glacial period, which, due to low agricultural suitability, have remained forested while the surrounding areas have been cleared and farmed (Johnston et al. 2008). Presently, agriculture is common along the southern fringes of the forest boundary and in the past was often classified as a

part of the Aspen Parkland, while forestry operations are scattered throughout this area (Strong and Leggat 1981).

Sand dune forests such as these owe their existence to low water tables that result from the rapid infiltration of moisture down through the sand. This infiltration shifts the competitive advantage away from grasses and to deeper-rooted shrubs and trees (Henderson et al. 2002). Most of the stands in the Island Forests are dominated by either jack pine (*Pinus banksiana*) or trembling aspen (*Populus tremuloides*). However, white spruce (*Picea glauca*), black spruce (*Pinus mariana*), balsam poplar (*Populus balsamifera*), and tamarack (*Larix laricina*) are also present. Some exotic species also exist in small numbers on the landscape such as Scots pine (*Pinus sylvestris*). White spruce and balsam fir (*Abies balsamea*) are the potential climax species on mesic sites. Jack pine communities are common in the area, occurring on sandy parent material such as outwash or sand dunes. Poorly drained sites are vegetated by an overstory of black spruce with an understory of Labrador tea, cowberry, and mosses (Moss 1953). The 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. Open and treed muskegs along with brush and grassy regions are also found within these forests. The Island Forests in Saskatchewan are located close to Prince Albert. There are four distinct Island Forests in this region: Canwood, Nesbit, Fort à la Corne, and Torch River (Figure 1). These forests are important to Saskatchewan because they unique landscapes that provide areas for recreation, wildlife habitat, support small forestry operations, and represent areas of cultural and spiritual importance to First Nations people. 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).

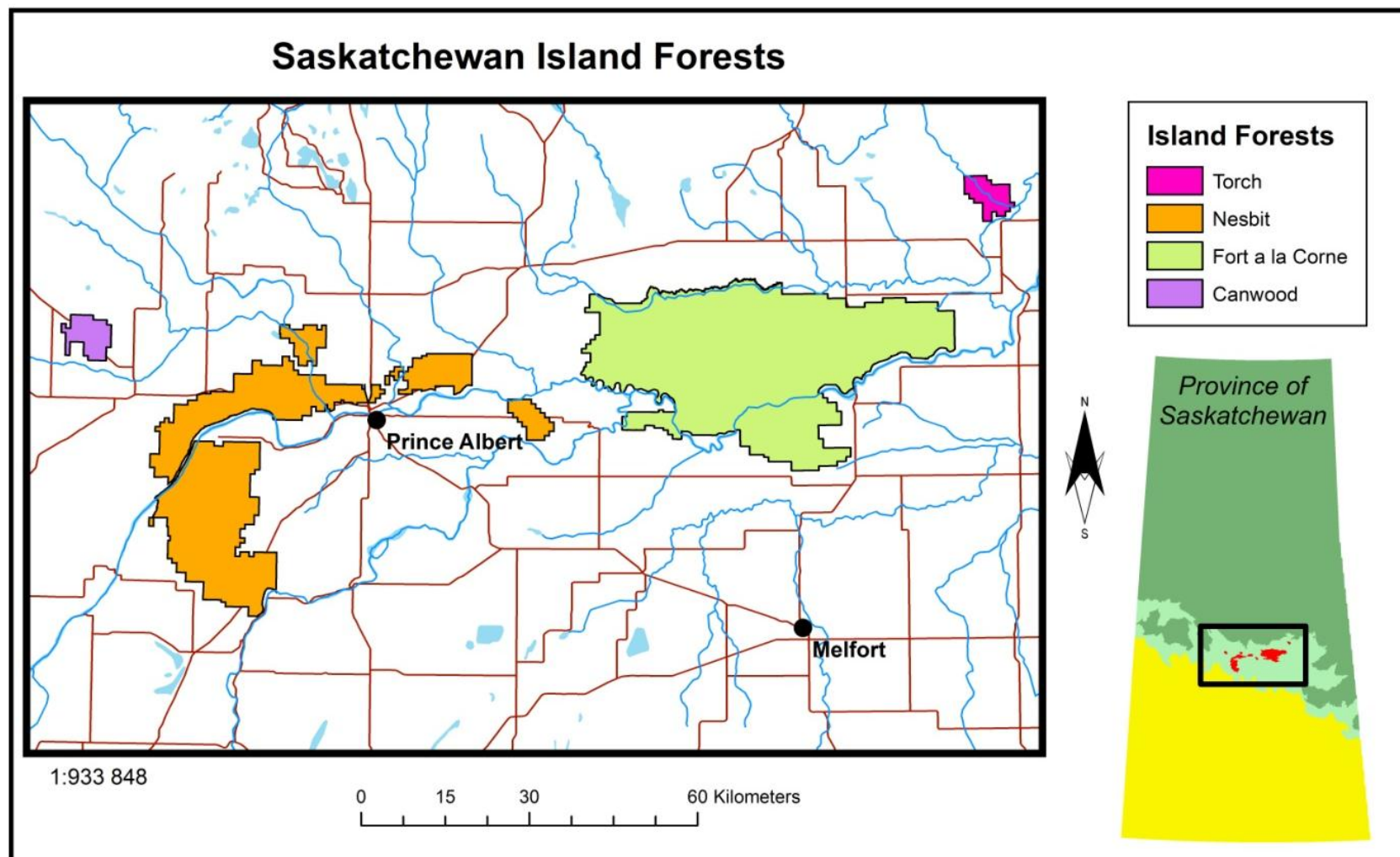
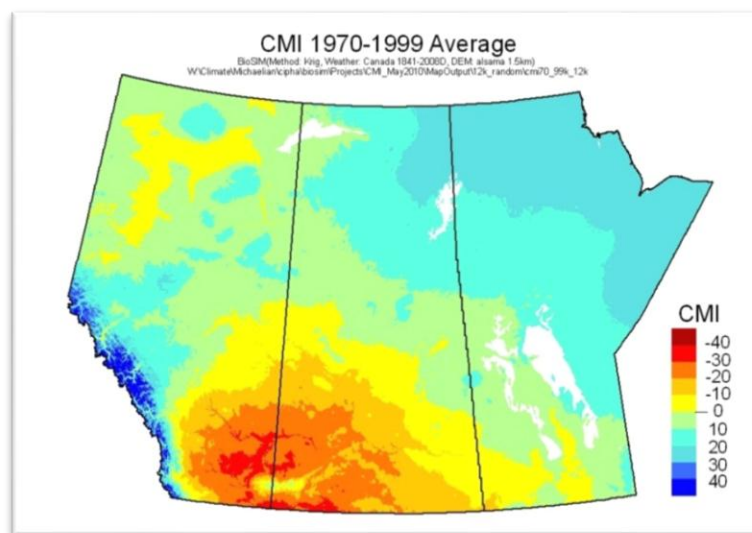


Figure 1: Location of the Island Forests in the Province of Saskatchewan, Canada

The Island Forests represent the southernmost extreme of the boreal forest. 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 almost exactly aligns with the southern boundary of the boreal forest across Alberta, Saskatchewan, and Manitoba (Figure 2). Therefore, positive index values support continuous forest cover while negative values support grassland/aspen parkland vegetation (Hogg 1994). This Island Forest is climatically at the brink of existence, representing the farthest southern extent of the boreal forest boundary. The lower CMI values for the Island Forests relative to the main boreal forest indicate that they could show climate change earlier than the boreal. Climate change modeling and past episodes of global warming show that the warming predicted over the coming century will likely shift the grassland/forest threshold northward, making the southern edge of the forest more suitable for aspen parkland or grassland vegetation (Hogg and Hurdle 1995, Iverson and Prasad 2001, Frelich and Reich 2010) and putting significant stress on our current island forest regions. There is already rapidly accumulating evidence showing direct documentation of changes in species and ecosystems linked to global climate change (McCarty 2001). The Island Forests at the southern edge of the boreal forest in Alberta, Saskatchewan, and Manitoba are close to urban centers, surrounded by agriculture, and are the focus of an array of overlapping land uses including: timber harvesting, wildlife habitat, livestock grazing, industrial developments, outdoor recreation and cultural values. A shift from forest cover to grassland as predicted by many scientific studies (Hogg and Hurdle 1995, Allen and Breshears 1998, Camill and Clark 2000, Chapin III et al. 2004, Parmesan 2006, McKenney et al. 2007, Olsson 2009, Michaelian et al. 2010) would drastically affect many of these land uses. The Island Forests importance is escalated when they are considered as an "early warning system" for the impact 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 and monitoring networks to ensure their existence. These regions are also at risk due to increasing droughts, fire, insects, disease, 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 need to be adopted soon.



**Figure 2: Average Climate Moisture Index (CMI) during 1970-1999 at a 1.5km resolution across the Canadian Prairies (Hogg 2010)**

The following sections provide a list of vulnerabilities that may potentially affect the Island Forests. Alberta's Climate Change Adaptation Framework (Sustainable Resource Development 2010) was adopted in this report to help outline the vulnerabilities and adaption options in a clear and concise manner. This framework was developed by Alberta Sustainable Resource Development (ASRD), which manages Alberta's lands, forests, fish and wildlife. The framework is designed to guide the user through a process of understanding sensitivities and existing adaptive capacity, which are then used to assess vulnerabilities and help to prioritize key climate change risks according to their likelihood of occurrence and magnitude of their impacts (Sustainable Resource Development 2010).

## **The Degree to Which the Island Forests are Sensitive to Climate Change**

Climate change has the potential to affect Canada's tree species physiology, phenology and distribution (Hughes 2000). Altered forest growth, insect pest and disease outbreaks, wildfires, forest disturbance regimes and species distributions are predicted to occur (Flannigan et al. 2000, Flannigan et al. 2001, Logan et al. 2003, Chapin III et al. 2004, Johnston et al. 2006) and will impact resource-dependent communities and the livelihoods of workers and families (NRTEE 2010). Climate change is a pervasive and inescapable force that is already affecting Canada's forests: in Alaska, Russia and the Canadian boreal forests there is a positive trend in area burned annually (Soja et al. 2006). This increasing trend in fire activity is occurring despite increased areas under fire suppression and more efficient fire suppression techniques, suggesting that fire activity is already increasing as a result of greenhouse warming (Gillett et al. 2004, Soja et al. 2006).

Furthermore, fire plays a major role in the carbon dynamics of the circumboreal region, releasing large amounts of carbon into the atmosphere. This positive feedback has the potential to be a major factor in a changing climate, whereby increased carbon emissions results in a warmer and drier climate, which will in turn create conditions conducive to more fire (Soja et al. 2006). In recent years, broad-scale insect infestations have been documented in Alaska (U.S. Department of Agriculture 2005) and British Columbia (Nealis and Peter 2009, Wulder et al. 2010). These outbreaks were in part caused by warming temperatures which allowed the insects to increase their historical range or complete their life cycle in one rather than two years, causing a shift in the balance between insects and tree defense in the favor of the insect. Since the 1980s, aspen has been suffering from dieback and periods of slow growth, especially along the southern edge of the boreal forest (Figure 3) (Natural Resources Canada 2011). This dieback is caused by interacting effects of severe drought and defoliation by insects. A recent severe, regional drought (2001-2002) in western Canadian aspen forests caused substantial dieback, decreases in growth and forest health (Hogg et al. 2008). Forests under drought stress are more susceptible to insects, disease, and fires which will all be more frequent under a drier, warmer climate (Hogg and Bernier 2005, Volney and Hirsh 2005). A similar occurrence has been documented on all continents except Antarctica. Over the past 10 years, the death of forest trees due to drought and increased temperatures has caused widespread forest mortality in many biomes (Romm 2011). This has been termed "Sudden Aspen Decline" which 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 (Worrall et al. 2010). Sudden aspen decline was also observed in Colorado starting in 2004, and by 2008 over 220,000 ha, or 17% of the aspen cover in the state, was



affected. Sudden aspen decline has led 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). The effects of climate change are extensive and also interactive, for example, increased warming temperatures can lead to drought which can make forests more vulnerable to insect attack and fire.



**Figure 3: Aspen dieback in Saskatchewan. August 2004. Photo: Michael Michaelian, Canadian Forest Service (Natural Resources Canada 2011)**

Modeling analysis for this region shows that the future moisture availability may become similar to the climate in southern Saskatchewan (e.g. Swift Current), and tree growth could decline by up to 30% (Johnston et al. 2010b). Winter temperatures with a minimum of  $-39^{\circ}\text{C}$  have declined in the past three decades, and will likely decline further with predicted climate change (Johnston et al. 2010b). This low temperature threshold limits the reproduction of mountain pine beetle and the parasitic dwarf mistletoe, both pests of jack pine (Johnston et al. 2010b) and as the number of days in which this minimum temperature occurs decline, the survivability of pests over the winter increase. Additional vulnerabilities include the old age classes in the Island Forests, which make this region more susceptible to pests. Nearly 60% of the forest is more than 70 years old, and 24% is between 50 and 70 years old (Johnston et al. 2010b). The multitude of vulnerabilities makes the risk of climate change impacts on this region quite high.

In order to develop a comprehensive vulnerability assessment and adaptation strategy, the sensitivity of the system to climate change and multiple disturbances must first be established. The creation of a master-list of ecosystem services (Table 1) identifies all the critical ecosystem services and socio-economic sectors that are depended upon or impacted by climate change discussed above. This list was created from a literature review of the current scientific information on the effects of climate change and its impacts on boreal forests (see Qualtiere 2011 for more details).

**Table 1: A master list of all the key ecosystem services vulnerable to climate change in the Island Forests of Saskatchewan**

Ecosystem Services	Projected Climate Change impacts	References
Water and Climate Regulation	Drought and excessive moisture; changes in extreme events	Mattson and Haack 1987, Hogg and Schwartz 1995, Allen and Breshears 1998, Sauchyn et al. 2003, Breshears et al. 2005, Hogg and Bernier 2005, Hogg and Wein 2005, Hogg et al. 2006, Rouault et al. 2006, Hogg et al. 2007, Hogg et al. 2008, Marchildon et al. 2008, Mealing 2008, Adams et al. 2009, Michaelian et al. 2010, Dai 2011
Water and Climate Regulation	Changes in extreme events occurring more often and widespread	Meehl et al. 2000, Diffenbaugh et al. 2005, Beniston et al. 2007, Jentsch et al. 2007
Habitats and Landscapes	Creation of new habitat types	Pernetta et al. 1995, Harris et al. 2006, Matthews et al. 2011, EPA 2012
Habitats and Landscapes	Loss of forest habitat due to shifting ecosystems (grassland>forest)	(Allen and Breshears 1998, Skov 2000, Shafer et al. 2001, Chapin III et al. 2004, Chiang et al. 2008, O'Neill et al. 2008, Schneider et al. 2009, PARC 2010)
Pests	Increasing invasive species, insects and diseases Potential increase in epidemics like Mountain Pine Beetle	Ives 1981, Anderson et al. 1987, Fleming 1996, Williams and Liebhold 1997, Fleming and Candau 1998, Volney and Fleming 2000, Harrington et al. 2001, Hogg 2001, Bale et al. 2002, Hogg et al. 2002, Allard et al. 2003, Dukes et al. 2009, Cullingham et al. 2011
Timber	Increasing frequency, intensity, and extent of forest fires	Anderson et al. 1987, Flannigan and Van Wagner 1991, Stocks 1993, Wotton and Flannigan 1993, Bergeron and Flannigan 1995, Kasischke et al. 1995, Fosberg et al. 1996, Bergeron and Leduc 1998, Flannigan et al. 1998, Peng and Apps 1999, Churkina and Running 2000, Flannigan et al. 2000, Flannigan et al. 2001, Sohngen et al. 2001, de Groot et al. 2002, Flannigan et al. 2002, Gillett et al. 2004, Hogg and Wein 2005, Kang et al. 2006, Geilsenan 2007, Balshi et al. 2009b, BC Ministry of Forests and Range Wildfire Management Branch 2009, Flannigan et al. 2009)
Timber	Regeneration failure due to drought, fire, and heat	Hogg and Schwartz 1995, 1997, Mohan et al. 2007, Future Forest 2011
Timber	Reduced tree growth and survival due to drought	(Joyce et al. 1995, Auclair et al. 1996, Kimball et al. 1997, Peng and Apps 1999, Churkina and Running 2000, Medlyn et al. 2001, Hogg et al. 2002, Andalo et al. 2005, Hogg et al. 2006, Kang et al. 2006, Rweyongeza et al. 2007, Chiang et al. 2008, Hogg et al. 2008, O'Neill et al. 2008, Wayson et al. 2009, Rweyongeza et al. 2010, Bernier 2011, Cortini et al. 2011)



Ecosystem Services	Projected Climate Change impacts	References
Timber	Loss of revenue from shift and net depletion of commercial forest land base	Sohnngen et al. 1999, Churkina and Running 2000, Sohnngen et al. 2001, Geilsenan 2007
Habitats and Landscapes	Shifting forest ecosystem types	(Allen and Breshears 1998, Chapin III et al. 2004, Chiang et al. 2008, PARC 2010)
Cultural/Spiritual	Loss of aboriginal lands of cultural and spiritual importance; traditional land uses	Qualtiere 2012
Genetic Resources	Loss of species	(Farnum 1992, Ledig 1992, Ledig and Kitzmiller 1992, Garcia-Ramos and Kirkpatrick 1997, Rehfeldt et al. 1999, Beaulieu and Rainville 2005, Rweyongeza et al. 2007, Eckert et al. 2008, Kramer et al. 2008, Howe and St. Clair 2009, Rweyongeza et al. 2010)
Recreation and Tourism	Loss of aesthetic quality	Qualtiere 2012
Recreation and Tourism	Decrease in recreation opportunities like ATV use, cross country skiing, horseback riding and snowmobiling	Qualtiere 2012
Carbon storage	Decreased growth and loss of tree species could result in decreased storage of carbon	Black et al. 2000, Alig et al. 2002, Balshi et al. 2009a

## Current Policies and Programs Taken to Adapt to Climate Change

An assessment of current activities is important to note when determining the vulnerability of a system. Adaptive capacity is a key component of any vulnerability assessment because it assesses the ability of the human system (or ecosystem) to adapt to the impacts of climate change. Assessing adaptive capacity may even help identify and address sources of vulnerability in forest-dependant social and economic systems (Johnston et al. 2010b). The higher the current adaptive capacity, the less vulnerable that system is to potential negative impacts of climate change because it already has measures in place to deal with impacts. While the scientific literature has covered adaptive capacity to some extent, research regarding adaptive capacity and adaptation activities is rare in the forest science field. On the ground there may actually be adaptation practices occurring, but it is generally not documented and therefore discussions are required with practitioners who may be using or beginning to consider these types of activities (Johnston et al. 2010b). Adaptation activities currently occurring in the Island Forests of Saskatchewan are listed in Table 2. Four categories of adaptation are used to identify and organize potential and actual adaptation options: Governance, People, Technology, and Process:

Governance	Options that address management, policies and processes to direct the activities of the organization, and include policy, resource decisions and facilitation of cross-organization relationships
People	Options that improve the capacity and capabilities of individuals within the organization and also look beyond the organization to external stakeholders, expertise inventory
Technology	Options that involve the application of science to adapt to the environment, such as climate modeling software, GIS, field equipment, monitoring equipment and infrastructure
Process	Options to address how work is done in an organization. Processes for climate change adaptation include development and deploying strategies, identifying and assessing risks, responding to risks, designing and testing measures, monitoring and re-evaluating progress, and continuous improvement

**Table 2: Inventory of existing policies and programs already in place to manage adaptation in the Island Forests of Saskatchewan**

Capabilities	Adaptation Activities
Governance	<ul style="list-style-type: none"> <li>• Fire bans implemented during dry seasons</li> <li>• Creation of fuel management project by industry to mitigate wildfire risk</li> <li>• Forest Management Plans include climate change strategies</li> <li>• Operating plan incorporates climate change strategies</li> <li>• Industry has developed Best Management Practices to protect themselves from starting fires (e.g. weather must be considered first before high risk burning/welding can occur, and a water source must be present)</li> <li>• Management of the Island Forests has been given to the Saskatchewan Research Council which required a devolvement of management to a 3<sup>rd</sup> party</li> </ul>
People	<ul style="list-style-type: none"> <li>• Saskatchewan Environment has appointed a forest adaptation expert</li> <li>• Sustainable Forestry Education</li> <li>• Climate change branch within the provincial government of Saskatchewan (located in Regina)</li> <li>• Provincial work plan is linked with SRC and others doing climate change work</li> <li>• Climate Change Science Group – located in Prince Albert</li> <li>• Climate Change Task Force created by the Canadian Council of Forest Ministers are doing work and training concerning climate change and adaptation</li> <li>• Climate change workshops are held for the Forest Service Branch</li> <li>• Canadian Institute of Forestry holds e-lectures, publishes research articles and helps practitioners learn more about climate change</li> </ul>
Technology	<ul style="list-style-type: none"> <li>• Considering the use of Wireless Sensor networks placed throughout the Island Forests to record environmental parameters for use in modeling and keeping</li> </ul>

Capabilities	Adaptation Activities
	<ul style="list-style-type: none"> <li>track of climate change</li> <li>A regeneration experiment is currently underway in the Island Forests looking at potential new species that might better survive under future climate change</li> <li>Archived weather from monitoring stations keeps track of weather conditions for long periods of time. This is done remotely and data is posted on a website which can help track fire and climate change over time</li> <li>BOREAS project lasted for 3 years and produced a wealth of tree physiology and climate data for the boreal forest region, suitable for use in forest ecosystem models applied to the Island Forests</li> <li>Routine monitoring done on forest trends, harvest and fire</li> </ul>
Process	<ul style="list-style-type: none"> <li>Standard Operating Procedures for forest management were written with additions added regarding climate change</li> <li>Changes in tenure arrangements including severing the relationship between industrial facilities and forest management. This will allow a stronger focus on forest management by more specialized managers, increasing adaptive capacity. Surveys done by SRC field technicians of the Island Forest region</li> <li>Field Trials such as: regeneration, non-native species and provenance tests for jack pine</li> <li>Salvage harvesting of blow-down forests leads to creation of new techniques because current equipment is only designed for removing upright trees</li> <li>Strategies are being developed with regards to climate change scenarios</li> <li>Tracking of Values, Objectives, Indicators, and Targets in forest management plans; there are currently 38 indicators related to regeneration success, timber volumes, burn severity and others.</li> </ul>

## Projected Climate Change Impacts that Could Affect Ecosystem Services in the Island Forests

In order to evaluate the climate change impacts on the Island Forests it is important to collect information regarding the climatic conditions in the region that may change in the future. This review documents the latest research on climate change and potential impacts in order to support future decision making and communicating the results to a wider audience (Sustainable Resource Development 2010). Table 3 contains the projected impacts of climate change on the Island Forest region. These impacts are relevant to the larger boreal forest but were also assumed to be similar for the southern boreal fringe and consequently, the Island Forests. Specific information for the area of interest is included when available.

**Table 3: Projected impacts on the Island Forests of Saskatchewan**

Climate Variable	Projected Change (+/-)	Expected change and timing	Expected seasonal changes	Confidence rating	Source
Annual Temperature	Increase	4.2°C - 4.9°C under a doubling of atmospheric CO <sub>2</sub> by the end of the century	Increases in mean and min daily maximum temperatures. Higher winter temperatures and earlier snow melt in the spring	High Confidence  Surface air temperature is particularly well simulated, with nearly all models closely matching the observed magnitude of variance and exhibiting a correlation > 0.95 with the observations	(Hogg and Hurdle 1995, IPCC 2001b, NRTEE 2010)
Annual Precipitation	Increase/Decrease	11% increase under a doubling of atmospheric CO <sub>2</sub>	Increase will not be enough to compensate for the increase in warming.  Less in summer with more as intense events	Low Confidence  Simulated variance of precipitation is within ±25% of observed	(Hogg and Hurdle 1995, IPCC 2001b)
Annual Soil Moisture	Slight to large decrease	-1 to -15% change in soil moisture	Increases in aridity for the mid to high latitudes in summer months	Medium Confidence  Modeling results use a mixture of temperature and precipitation data to predict % of soil moisture	(Seneviratne et al. 2002) (Wetherald and Manabe 1999)
Winter Temperatures	Increase	Number of days with minimum temperatures below -39°C has declined in the past three decades	Earlier spring and longer fall seasons may allow for a more pests and fire	High Confidence  There is already evidence of this happening	(Johnston et al. 2010b)
Fire	Increase in intensity and frequency and area	The average area burned per decade could increase by a factor of 3.5 to 5 by the last decade of this century. The average forest area burned in western wildfires could increase by 200% to 400% by	Fire season may start earlier and end later  estimated the length of the fire season would be an average of 30 days (22%) longer across Canada and up to 51 days longer in British	High Confidence  There is already evidence of increased fire and it is an eventuality if temperatures rise and precipitation decreases	(Flannigan and Van Wagner 1991, Wotton and Flannigan 1993, Price and Rind 1994, Flannigan et al. 2005, Soja et al. 2006, Flannigan et al. 2009,

Climate Variable	Projected Change (+/-)	Expected change and timing	Expected seasonal changes	Confidence rating	Source
		the end of this century	Columbia.		Wotton et al. 2010)
Drought	Increase in intensity and duration	A doubling to quadrupling in the frequency of droughts lasting 4–6 months for Western North by the end of the 21 <sup>st</sup> century. Smaller increases in the frequency of long droughts lasting 12 months or more	In the Prairies, lower spring and summer stream flows are likely to occur in what is already a dry region, increasing both soil water deficits and surface water deficits.	High Confidence  The region of interest has been dry in the past and is very vulnerable to slight changes in water availability due to the sandy soils that span the region	(Sauchyn et al. 2005, Burke et al. 2006, Bonsal and Regier 2007, Martz et al. 2007, Sheffield and Wood 2007)
Insects & Disease	Increase in intensity and frequency for some	Increases in growth, reproduction, dispersal, transmission rates, infection phenology and overwinter survival as temperatures increase	Earlier outbreaks as spring season starts earlier. Warmer winters allows forest pathogens to increase their range and survival rates (e.g.: Dwarf Mistletoe & Mountain Pine Beetle)	Medium Confidence  There is already evidence of insect species expanding their range	(Fleming 1996, Volney and Fleming 2000, Hogg et al. 2002, Dukes et al. 2009, Johnston et al. 2010b)
Regeneration	Decrease	Regeneration of tree species (especially conifers) is expected to be significantly reduced in the southern boreal forest if the CMI decreases to less than -15	Future warming of 2°C would represent summer temperatures associated with extreme levels of stress on trees	High Confidence  Lower soil moisture and heat stress will cause reduced regeneration. There is already evidence of reduced regeneration in the island forests	(Hogg and Schwartz 1995, Chapin III et al. 2004, Bendzsak 2006)
Productivity	Increase in moist areas/Decrease in dry regions	The direction and degree of change are uncertain due to many factors changing simultaneously and will be highly dependent on site characteristics	Positives = CO <sub>2</sub> fertilization, longer growing season, increased Water Use Efficiency, accelerated growth  Negatives= increased fire, drought, temperature, insects	Low Confidence  Studies are ambiguous on the effects of climate change on the boreal forest. It will likely depend greatly on site characteristics and species	(Bernier 2011)
Carbon storage	Decrease	Carbon Budget Model of the Canadian Forest	Increased summer fires, reduced productivity,	High Confidence  There are more	(Kurz et al. 2009)

Climate Variable	Projected Change (+/-)	Expected change and timing	Expected seasonal changes	Confidence rating	Source
		Sector has projected that the managed forests of Canada could be a source of carbon between 30 and 245 Mt CO <sub>2</sub> yr <sup>-1</sup> during the first Kyoto Protocol commitment period (2008-2012).	harvesting practices and insect outbreaks can all decrease the ability of forests to store carbon	Impacts that will cause a reduction in carbon storage capabilities in the forest opposed to capture such as an increase in fire, pests, disease and drought	
Species shift	Decrease (up to 20%)	Shift of southern edge of the boreal forest northward by the end of the century  Large shifts are expected in the distribution of Canada's forest biomes over the next 50 years due to climate change	Effects may extend the existence of trees once climatic zones have shifted	Medium Confidence  Many studies predict that there will be a shift in species. However the extent and timing of such events are difficult to predict and there will probably be remnants lagging behind climate shifts. The Island Forests are isolated and therefore their ability to expand northward will be limited	(Hogg and Hurdle 1995, Henderson et al. 2010)

## Scope of the Current Assessment

The forestry component of the Prairie Regional Adaptation Collaborative was initiated in 2010. The forestry component deals with the vulnerability of the southern boreal forest, specifically the Island Forests, and the implications for forest management planning and forest policy in this region. Deliverables within this assessment include a **vulnerability assessment** for the southern boreal forest, focusing on drought and associated impacts (e.g. forest fires, insect and disease outbreaks). A **modeling approach** to characterize the severity of impacts on this ecosystem under climate change, using modeling techniques over the specified landscape, and **identifying potential adaptation options** in the categories of people, process, technology and governance.

A vulnerability assessment is done using the framework outlined by SRD's Climate Change Adaptation Framework Manual (Sustainable Resource Development 2010). The initial vulnerability assessment is created using a literature review of current scientific knowledge. Much of this initial assessment is very general in nature as there is not very much information specific to the Saskatchewan Island Forests that border the boreal forest fringe in the south. Therefore, a modeling approach was chosen to delve deeper into climate change and its potential impacts on these Island Forests. This modeling procedure

gives an estimated range of future impacts based on the Canadian Regional Climate Model (CRCM) and this provides better information to develop adaptation strategies for this region. The CRCM version 4.2.3 is driven by the Canadian Global Climate Model version 3, following IPCC “SRES A2” GHG scenario over the North-American domain with a 45-km horizontal grid-size mesh, 29 vertical levels and spectral nudging of large-scale winds. The source of the data for the CRCM was generated and supplied by the Ouranos Climate Simulation Team via the Canadian Centre for Climate Modeling and Analysis data distribution web page (Music and Caya 2007). The forest ecosystem model chosen is a landscape model which can take into account climate change, changes in productivity, increased fire on the landscape, while simulating succession and disturbance dynamics. Emphasis is on considering multiple sources of vulnerability collectively and in a climate change adaptation context that can be useful to forest managers and policy makers to effectively cope with climate change.

## 2. 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 of that system decreases (Santoso 2007). Turner II et al. (2003) describe vulnerability as a function of three overlapping characteristics: **exposure**, **sensitivity** and **adaptive capacity**. This concept was further developed by Metzger et al. (2006) by expressing it mathematically, where vulnerability (V) is a function of exposure (E), sensitivity (S) and adaptive capacity (AC):

$$V = f(E, S, AC)$$

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 more forest fires), while adaptive capacity (AC) is the ability of a human system 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, 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).

### Sensitivity of the Island Forests to Climate Change

The projected climate change impacts on the ecosystem services in the Island Forest region and collection of current adaptation activities developed in the above sections is used to qualitatively assess the degree to which the identified ecosystem services are sensitive to climate change impacts (Sustainable Resource Development 2010). A sensitivity matrix (Figure 4) was used to determine the degree of sensitivity and the rationale for each selection was documented in Table 4.

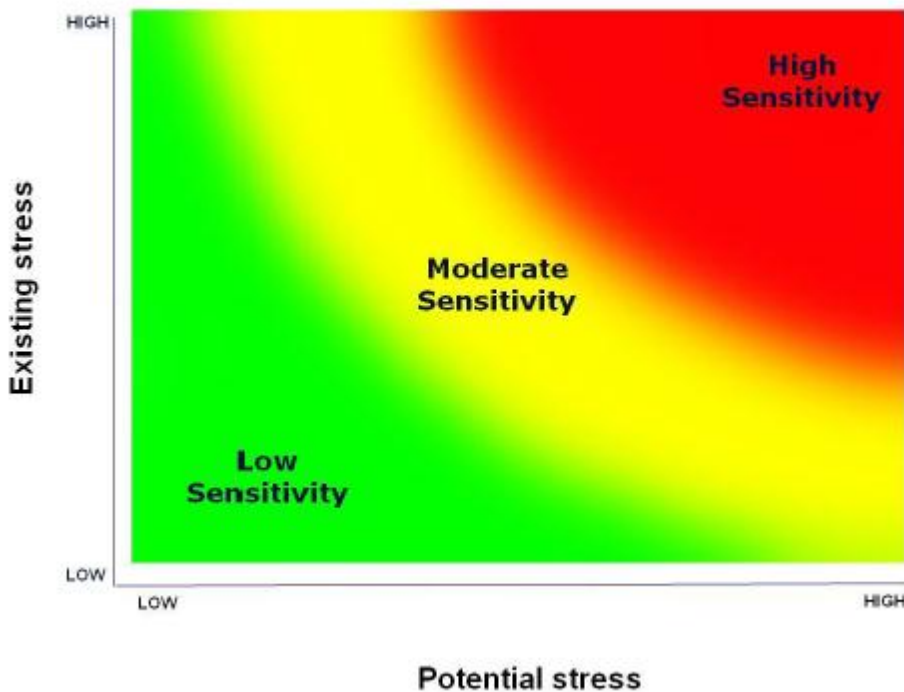


Figure 4: Sensitivity matrix showing a range of values from low to high for existing and potential stress on the system in question (obtained from Sustainable Resource Development 2010).

Table 4: Sensitivity Analysis. Using the degree of sensitivity from existing and potential stress, the overall degree of sensitivity is determined using the matrix in Figure 4.

Ecosystem Services	Existing Stress	Degree of sensitivity from existing stress	Potential Stress	Degree of sensitivity from potential stress	Degree of sensitivity
<b>Water and Climate Regulation:</b> Extreme Drought	Drought is already affecting regions of the southern boreal forest fringe causing aspen dieback and reduced regeneration in some areas	Moderate	Increases in drought frequency and intensity as climate change causes higher temperatures and reduced moisture	High	High
<b>Water Regulation:</b> Extreme Moisture	Since the 1990s, there have been a total of 22 extreme flooding events in Saskatchewan	Low	GCM outputs for extremes of future climate (Kharin and Zwiers 2000) suggest increased climate variability and more frequent extreme events, including a greater frequency of flooding and	Moderate	Low - Moderate



Ecosystem Services	Existing Stress	Degree of sensitivity from existing stress	Potential Stress	Degree of sensitivity from potential stress	Degree of sensitivity
			severe drought. Warmer temperatures increase the likelihood of extreme rainfall events (Groisman et al. 2005).		
<b>Habitats and Landscapes:</b> species shift and fragmentation	Species within the island forests are limited geographically by the low frequency of suitable habitats nearby and fragmentation from larger boreal forest area. Area is surrounded by agricultural land	Low	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 and putting significant stress on current Island Forest regions. This could result in habitat loss and shifts in forest ecosystem types. Some studies predict that this region could be converted to grasslands overtime	Moderate-High	Moderate
<b>Pest regulation:</b> Insects and Disease	The Saskatchewan Island Forests are infected with Dwarf Mistletoe (around 1/3 of the jack pine are infected), larch beetle, jack pine and spruce budworm, aspen canker, aspen dieback and aspen heartrot	High	Climate change is likely to increase infection rates of certain pests because of an increase in mild winter temperatures. Range is likely to expand northward. Mountain Pine Beetle (MPB) is also a potential danger to jack pine stands in the island forests as it has been proven that jack pine can act as a host for MPB.	High	High
<b>Timber:</b> increases in fire frequency and intensity	Since the 1970s, the average area burned by forest fires in the boreal forest has doubled despite improvements in technology, fire detection, and suppression	High	Fire frequency is predicted to increase over the next century which will ultimately lead to a loss of timber. There is predicted to be a four-fold increase in the highest Head Fire Intensity class in the Island forests under a	High	High

Ecosystem Services	Existing Stress	Degree of sensitivity from existing stress	Potential Stress	Degree of sensitivity from potential stress	Degree of sensitivity
			doubling of CO <sub>2</sub> . This will cause severe fire conditions and make fire suppression very difficult, if not impossible		
<b>Timber:</b> reduced natural regeneration	Regeneration after cutovers and following fires in the Island Forests is low with 16% of the cutover land Not Sufficiently Restocked	Moderate	Climate change is predicted to reduce regeneration through increased drought, pests and fire	High	High
<b>Timber:</b> cumulative effects of impacts	Synergistic effects of drought, insects, disease and fire caused extensive mortality of aspen groves across the aspen parkland in 1961 and again following the 1988 drought and more recently in 2001-2003	High	Loss of timber and productivity of forested areas due to increased fire and forest health damaging agents under climate change can lead to significant loss of forest productivity and timber supply	High	High
<b>Timber:</b> supply and revenue	Lempriere et al. (2008) 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	Moderate	From 2041-2100 impacts will become negative, and timber supply will be reduced. However, this may greatly depend on which scenario you run and whether you take into account CO <sub>2</sub> fertilization and water use efficiency	High	High
<b>Cultural/Spiritual</b>	Areas for First Nations people to collect traditional medicinal plants and habitat have been reduced	Low	Many of these traditional plants may be at risk under climate change if their ecosystems cease to exist or shift out of their range	High	Moderate
<b>Genetic Resources</b>	Human caused habitat fragmentation of the area has isolated the island forests entirely from the greater boreal forest reducing their ability to adapt to changes in the environment (lack of gene pool)	Low	Loss of within-species genetic resources can be more pronounced as climate change may extirpate many tree species unable to relocate to more favourable climates. However, improved seed stock and assisted migration may help reduce the	Low - Moderate	Low

Ecosystem Services	Existing Stress	Degree of sensitivity from existing stress	Potential Stress	Degree of sensitivity from potential stress	Degree of sensitivity
			sensitivity		
<b>Carbon storage</b>	Study sites in the southern boreal forest (BOREAS study; Sellers et al. 1995) found that aspen were able to sequester significantly more carbon due to warmer spring temperatures. Currently there are many decadent stands within the Island Forests that may act as a large carbon source. Also, due to the large mistletoe infestation, many jack pine trees are currently dying	Moderate	Increases in pests, fire, and other natural disturbances will play a large part in influencing the ability trees to store carbon. Loss of forest area predicted by shifting ecozones, especially in the boreal transitional zone can cause loss of carbon storage for this region, especially it is converted into grassland	High	High

## Adaptive Capacity of the Island Forests to Climate Change

Adaptive capacity describes the ability of an organization to accommodate and respond to changes in climate (Sustainable Resource Development 2010). Adaptive capacity is defined by factors that determine the ability and likelihood that forest managers will adapt in order to reduce current and potential future impacts (Johnston and Williamson 2007). Examples include: the flexibility and efficiency of institutions and policy, distribution and availability of financial resources, technological capacity and human capital (Smit and Pilifosova 2001). If an organization is able to respond and adapt to climate change impacts it is considered to have a high adaptive capacity and the vulnerability of this system is reduced. In Table 5 below, the ecosystem services within the Island Forests are listed along with the climate change impacts and any current adaptation activities that may be addressing the impacts. Most of the adaption responses are based on personal knowledge of Saskatchewan Forest Service officials (Qualtiere 2012) and additional references are noted within the table. Not all ecosystem services have adaptation responses. This portion of the vulnerability assessment is important to establish the current ability of the human system to address climate change and help determine what will be needed in the future. The qualitative ranking of the degree of organizational adaptive capacity is used as the second input into the vulnerability assessment and is determined using professional judgement and group discussions, on the degree to which the organization can adapt to the impact.

**Table 5: Adaptive Capacity Analysis**

<b>Ecosystem Services</b>	<b>Climate change impacts</b>	<b>Current adaptation response</b>	<b>Adaptive capacity</b>
<b>Water and Climate Regulation:</b> Drought	Increases in drought and warmer temperatures can cause decreased survival and regeneration of trees in the island forests in these low water-holding capacity soils	<p>Evaluation of conifer tree species alternatives for Island Forest Renewal. Some study plots are already planted (see Bendzsak 2006)</p> <p>New project underway looking at implementing provenance tests and exotic species that may be better adapted to climate changes in the future</p> <p>Forest Management Plans are attempting to increase retention of forest cover by 5%, help with regeneration challenges, and work with natural disturbance patterns</p> <p>Silviculture efforts include narrowing the window of planting time to help with survival rates of trees. Trees are no longer planted late in the season</p>	Moderate depending on length and intensity of future drought events
<b>Habitats and Landscapes:</b> species shift and fragmentation	Species within the island forests are limited geographically by the low frequency of suitable habitats nearby and fragmentation from larger boreal forest area. Area is surrounded by agricultural land and therefore species migration is difficult and there are no southern provenances to take their place	<p>Reforestation is now being done with better adapted populations more suitable to the region (species type remains the same)</p> <p>Forest Management Plans are now targeting diseased areas for harvest (e.g. mistletoe-affected stands) and new healthy stands are planted to replace them</p>	Moderate
<b>Pest regulation:</b> Insects and Disease	Large areas are currently affected by dwarf mistletoe and this may increase under climate change. There are also considerations of susceptibility to future mountain pine beetle outbreaks.	<p>Monitoring programs are in place to keep track of affected trees</p> <p>Improved harvesting guidelines by targeting affected areas and degrading stands for harvest and more harvesting of jack pine to mitigate the effects of future potential MPB attack</p>	<p>Moderate to Low</p> <p>(Low if MPB reaches the Island Forests)</p>
<b>Timber:</b> increases in fire frequency and intensity	Fire frequency and intensity is predicted to increase over the next century as the Island Forest region is considered to be a relatively large fire hazard	<p>Fuel management plan has been implemented to target high risk sites for mitigation</p> <p>Fire strategy modified response zones</p>	Low

Ecosystem Services	Climate change impacts	Current adaptation response	Adaptive capacity
	<p>due to its aging forests, dry climate and effects of dwarf mistletoe</p> <p>When fires start and climate conditions are very favorable to fire, often it is beyond control of forest fire managers</p>	<p>linked to climate change; Forest fire protection strategy</p> <p>Prescribed burns could be used but often they are too risky and carry a negative social response</p> <p>Implementation of a fire awareness such as FireSmart</p> <p>Upgrade aerial fleet</p>	
<b>Timber:</b> reduced regeneration	Regeneration is predicted to decrease further under climate change due to drought and low water holding capacity soils	<p>Evaluation of conifer tree species alternatives for Island Forest Renewal. Some study plots are already planted and testing non-native species that have some degree of invasiveness so that they might establish easier on sites (see Bendzsak 2006)</p> <p>New project underway looking at implementing provenance tests and exotic species that may be better adapted to climate change in the future</p> <p>Different types of site preparation can be used to help regeneration</p> <p>Timing of planting can be modified</p>	Moderate
<b>Timber:</b> cumulative effects of impacts	Negative impacts on tree growth due to long-term and short-term stressors arising from complex interacting impacts such as insects, drought, disease and fire	Upgrading FMPs, strategies and land use plans to include climate change	Low
<b>Timber:</b> supply and revenue	Timber production will likely be reduced in the Island Forests as growth rates and productivity will ultimately decrease under climate change impacts in this region	<p>Evaluation of conifer tree species alternatives for Island Forest Renewal. Some study plots are already planted (see Bendzsak 2006)</p> <p>New project underway looking at implementing provenance tests and exotic species that may be better adapted to climate changes in the future</p> <p>Suppressing fires</p> <p>Diversification of products could also increase supply on the landscape</p>	Moderate

Ecosystem Services	Climate change impacts	Current adaptation response	Adaptive capacity
Cultural/ Spiritual	First nations communities are worried that their traditional land uses in the Island Forests including medical herb gathering will be severely impacted by climate change	There are some initial discussion involving Beatty's First Nation to look at the effects of climate change on trapping, traditional plant gathering and wildlife habitat  Traditional sites have already been identified for protection	Moderate
Genetic Resources	Two main vulnerabilities are the loss of species and the loss of within species forest genetic resources	Implementing provenance tests may help maintain current species on the landscape and conserve genetic resources  Free planting	Moderate
Carbon storage	Older forest structure, death and dieback of forests and limiting growth caused by climate change can all lead to a decrease in carbon storage for this region.	Reforestation and removal of decadent and diseased stand and replace with healthy ones  Creation of a younger forest which is better suited to fend off disease and death  Accelerated harvest done before loss of trees occurs	Low

### Vulnerability of the Island Forests to Climate Change

The third and final portion in the vulnerability assessment step is to combine the results from the sensitivity and the adaptive capacity analysis to determine the degree of vulnerability to specific climate change impacts on each identified ecosystem service in the Island Forests. A vulnerability matrix (Figure 5) is used to establish the vulnerability of the system. This figure is used as a guide to determine the vulnerability ranking for each climate change impact shown in Table 6.

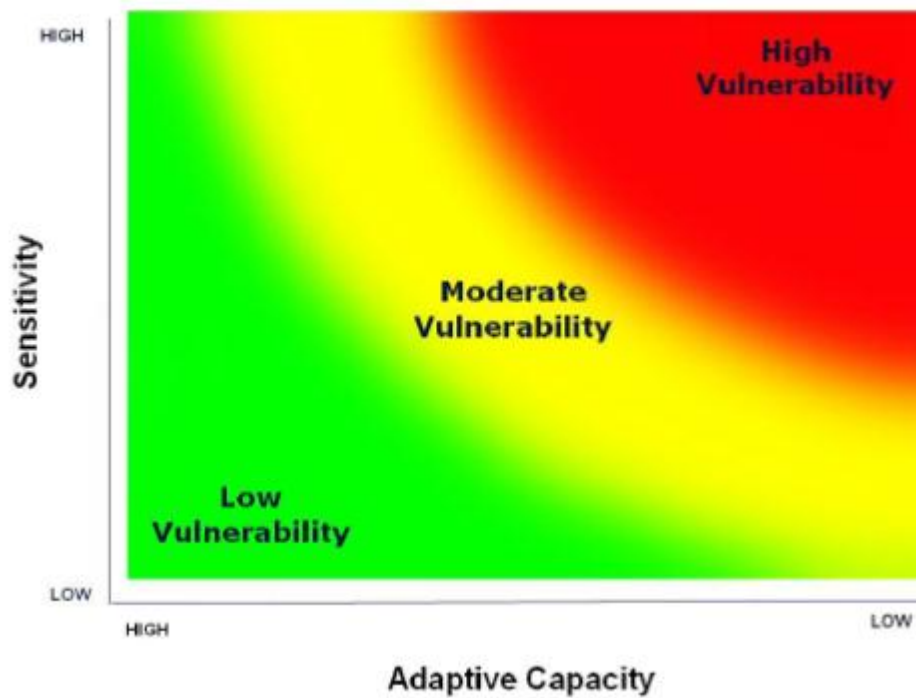


Figure 5: Vulnerability matrix (obtained from Sustainable Resource Development 2010)

Table 6: Vulnerability Assessment.

Ecosystem Services	Existing and potential impacts	Degree of sensitivity	Adaptive capacity	Vulnerability
Water Regulation	Drought and excessive moisture	High	Moderate	High
Habitats and Landscapes	Species shift and fragmentation	Moderate	Moderate	Moderate
Pest regulation	Insects and Disease	High	Low- Moderate	High
Timber	Increases in fire frequency and intensity	High	Low	High
	Reduced regeneration	High	Moderate	High
	Cumulative effects of impacts	High	Low	High
	Supply and revenue	High	Moderate	High
Cultural/ Spiritual	Loss of First Nations hunting, gathering and wildlife habitat	Moderate	Moderate	Moderate
Genetic Resources	Loss of species and the loss of within species forest genetic s	Low	Low	Low
Carbon storage	Declining bioproductivity and forest health	High	Low	High

## Conclusions

The majority of the ecosystem services in the Island Forests are highly vulnerable to climate change including: water regulation, habitats and landscapes, pest regulation, timber, and carbon storage. A vulnerability assessment is an important way to start establishing knowledge regarding potential vulnerabilities for an area of interest using observed data, such as expert knowledge and a literature review. Observed data are more transparent and thus more credible for decision-making. However, observed data cannot identify some very important risks of climate change, in particular in the medium and long term effects (Fussel 2009). Actual studies on how the Island Forests may be affected by climate change are rare and therefore most of the vulnerabilities must be assumed from literature covering the larger boreal forest. Many inferences can be made regarding the Island Forests due to its location on the forest margin, but they are really just best guesses. Many of the above impacts are in need of further investigation with a more detailed look at the area in question. Sophisticated model simulations can provide a much more detailed picture of future climatic risks (Fussel 2009). The interaction of ecological processes and environmental stressors are complex, and thus, models are needed that can represent dynamic communities, shifting species distributions and diverse disturbance regimes at appropriate spatial and temporal scales. A modeling approach was applied to this region which allows many of the climate change impacts on the Island Forest to be examined in this area. The model chosen is a spatially explicit model that can simulate multiple and interactive disturbances, including climate changes such as temperature and precipitation at a biologically meaningful resolution (Scheller et al. 2007). Modeling theoretically delivers a more detailed look at the Island Forests region under future climate change and gives us a range of probable futures and vulnerabilities. With more clearly defined ranges (e.g. how much fire will increase), better adaptation options can be developed that are more specifically aimed at the impact. The next sections detail the models chosen to look at the vulnerabilities of the Island Forests to climate change impacts.

## 3. Modeling Multiple Climate Change Impacts on the Island Forests

### Materials & Methods

#### ***Modeling Description***

A landscape-ecology approach was used to incorporate climate change and examine multiple vulnerabilities of the study area to climate change using the landscape disturbance model LANDIS-II (LANDscape Disturbance and Successional model) coupled with a forest ecosystem process model called Photosynthesis and Evapotranspiration (PnET-II). The output from these two models can provide details regarding biomass accumulation and spatial patterns of forest cover types (Mladenoff and He 1999) while modeling fire dynamics. These two coupled models have been proven to be a useful application to explore the interaction of climate change on forest succession and dynamics (He et al. 2002, Scheller and Mladenoff 2005, Xu et al. 2007, 2009).



### **PnET-II for LANDIS-II Model**

The PnET-II-for-LANDIS-II model generates estimates of aboveground net primary production (ANPP) and species establishment probability (SEP) inputs for LANDIS-II regarding each tree species on the landscape. These two parameters are needed for the operation of the LANDIS-II biomass extension. This model version was specifically designed to work with the LANDIS-II model, and programmed by Dr. Chonggang Xu based on PnET-II VB5.1, which is an improved version of the original PnET model (Aber and Federer 1992). Detailed information about the PnET model and its variations can be found on the PnET model website: <http://www.pnet.sr.unh.edu>, the PnET-II for LANDIS version can be downloaded from: <http://sites.google.com/site/xuchongang/pnetiiforlandisii>. Further documentation regarding this program can be found in Xu et al. (2009).

PnET-II is a process-based model of carbon and water dynamics in forest ecosystems (Aber and Federer 1992, Ollinger et al. 2002). This model uses a linear response of maximum net photosynthetic rate to foliar N concentration to calculate ANPP. PnET-II can include the effects of elevated CO<sub>2</sub> on forest production and the effect of CO<sub>2</sub> on water use efficiency through stomatal conductance (see Ollinger et al. 2002 for more details). The PnET-II model simulates the effect of climatic change on forest photosynthesis by applying an adjusting factor of light, temperature, water availability, water vapor deficit and CO<sub>2</sub> (Xu et al. 2009). SEP is calculated in the model by environmental adjusting factors of light, water availability, vapor pressure deficit for photosynthesis and growing degree days from the optimum growing degree-days for a specific species (see Xu et al. 2009 for more details).

The species-specific parameters for PnET-II include foliar nitrogen content, optimal photosynthetic temperature, maximum leaf mass area and leaf retention time (Table 7). The optimum photosynthetic temperature is calculated based on the median of mean July temperatures for species distributions in North America (Xu et al. 2007). Growing Degree Day maximum and minimum values are based on the species range of distribution and calculations from the LINKAGE model. Most parameters are from Scheller and Mladenoff (2005). Values for tamarack and the brush species were absent in literature, therefore, they were not included in PnET-II.

**Table 7: Main species attribute parameters used in the PnET-II model**

Species	GGDMin	GDDMax	OPT	FNC	MLMA	LRY
Jack pine	830	2216	19.9	1.10	200	2.25
White spruce	280	1911	17.8	0.80	170	4
Black spruce <sub>lowland</sub>	247	1911	17.7	0.80	170	4
Black spruce <sub>upland</sub>	247	1911	17.7	0.45	170	4
Balsam fir	560	2386	19.6	0.80	170	4
Aspen	743	2900	20	2.39	100	1
White birch	484	2036	18.8	2.39	100	1
Balsam poplar	555	2491	17.7	2.39	100	1

GGDMin, minimum growing degree days; GDDMax, maximum growing degree days; OPT, Optimum temperature for photosynthesis (°C); FNC, foliar nitrogen content (%); MLMA, maximum leaf mass area (g/m<sup>2</sup>); LRY, leaf retention (years)

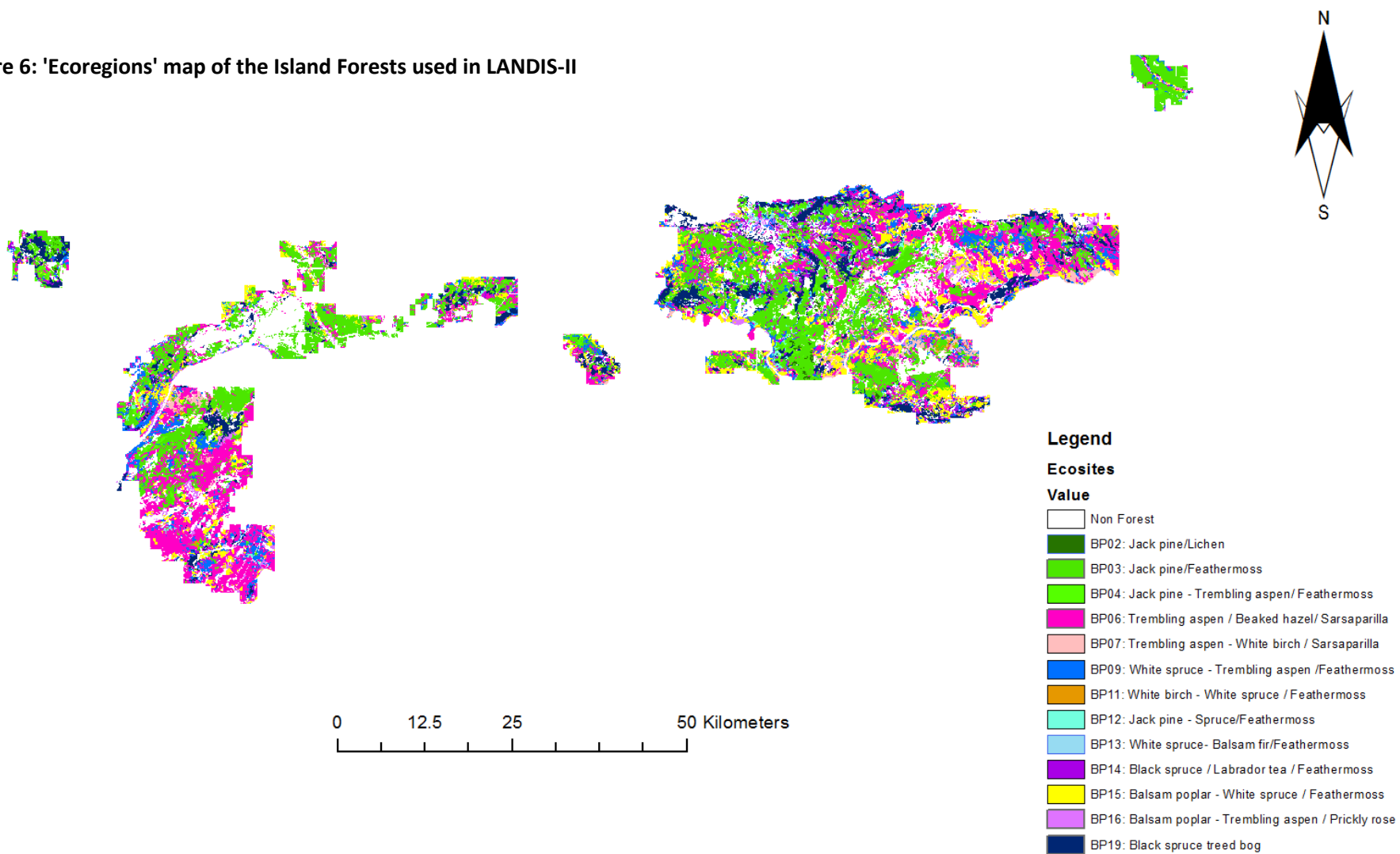
## **LANDIS-II Model**

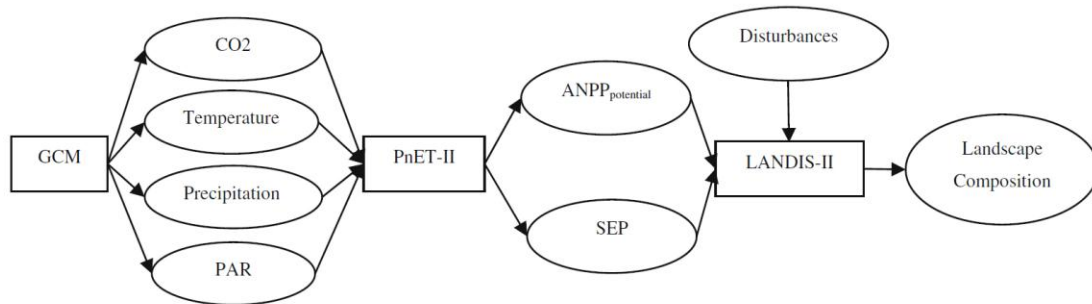
LANDIS-II is a spatially-explicit, stochastic model of forest landscape dynamics, including disturbance, succession and management. It is designed to allow a user to simulate long-term disturbances, including harvesting if desired (ArborVitae Environmental Services and KBM Forestry Consultants Inc. 2006). The model is maintained and developed at the Forest Landscape Ecology Laboratory at the University of Wisconsin at Madison, in collaboration with the US Forest Service Northeast Forest Experimental Station. The model can be downloaded from <http://www.landis-ii.org> and includes a user's manual so only a brief description of the model and data requirements are provided within this report.

LANDIS-II requires quite detailed landscape description data and includes the following processes: succession, seed dispersal, fire, wind, and harvest disturbance. The wind and harvest disturbance modules were not used in this project. Spatial inputs for LANDIS-II take the form of raster maps (50 m cell size in this study) and include land types, tree species cohorts (initially found in each cell), and fire regions. Each land type is stratified into areas of similar abiotic conditions, called "ecoregions", which have the same soil and climate conditions (Xu et al. 2009). To simplify the ecoregion classification scheme in this study, some land type classes were combined based on site similarities. This included bog and fen type regions which were not considered to be as significant due to their low importance to forestry managers, so there was no need to model them separately (see Table 8). The Island Forest landscape was composed of 13 land types which are shown in Figure 6. This model operates by tracking species and age cohort information at the site level while simulating non-spatial processes (species establishment and succession) and spatially interactive processes across sites (seed dispersal and fire). The forest landscape is driven by user-set life history attributes for each species, species establishment probabilities, and biomass growth rate determined by the maximum ANPP disturbances and spatial heterogeneity (Xu et al. 2009). Each cohort establishes and responds to disturbance as a function of its life history attributes, and in the case of disturbance, its age. The primary model output is maps depicting forest conditions, including species, age classes, aboveground biomass, disturbance types and their respective severities (Gustafson et al. 2010).

The LANDIS-II model simulates the forest-type composition response to future climatic change by modifying the species' competitive and colonization ability (Xu et al. 2009). In the LANDIS-II model, the species' competitive ability under future climate may change through modification of the growth rate determined by ANPP. The colonization ability may change through the modification of SEP, which defines the probability of seedling establishment under a specific climate (Xu et al. 2009). The PnET-II model provides the estimate of ANPP and SEP under future climates using climate model output data which incorporate the effects of climate change into the modeling framework (Figure 7).

Figure 6: 'Ecoregions' map of the Island Forests used in LANDIS-II





**Figure 7: Flow diagram of model coupling.** The ovals represent input/output variables. The rectangles represent models. ANPP<sub>potential</sub>, Potential/Maximum aboveground primary production; SEP, species establishment probability. ANPP<sub>potential</sub> and SEP may be modified by climate change and is estimated by the PnET-II model. The modification of ANPP<sub>potential</sub> is used to represent species' colonization ability response to climatic change. PAR, photosynthetic active radiation; GCM, global circulation model. Diagram from (Xu et al. 2011)

**Table 8: Final Ecoregion Classification**

Boreal Plain Ecosites	Description (Dominant vegetation and Soils)	Area (ha)	Proportion of landscape
Inactive	Water, Non Forested areas (including grasslands and shrubby areas)	43,409	19%
BP02	Jack pine/lichen: Moderately fresh sand	525	0%
BP03	Jack pine/feathermoss: Moderately fresh loamy sand	52,997	23%
BP04	Jack pine - trembling aspen / feathermoss: Moderately fresh sand	8,814	4%
BP06	Trembling aspen / beaked hazel / sarsaparilla: Fresh loamy sand	49,079	22%
BP07	Trembling aspen - white birch / sarsaparilla: Fresh loamy sand	4,686	2%
BP09	White spruce - trembling aspen /feathermoss: Fresh sand	16,915	7%
BP11	White birch - white spruce / feathermoss: fresh sand	487	0%
BP12	Jack pine - spruce/feathermoss: fresh loamy sand	2,915	1%
BP13	White spruce- balsam fir/feathermoss: Fresh sandy clay loam	34	0%
BP14	Black spruce / Labrador tea / feathermoss: Very moist sandy clay loam	6,340	3%
BP15	Balsam poplar - white spruce / feathermoss: Very moist silty clay loam	18,985	8%
BP16 & 17	Balsam poplar - trembling aspen / prickly rose: Fresh clay loam Manitoba maple - balsam poplar / ostrich fern: Moist silty clay loam	5,107	2%
BP19, 20, 22, 23,	Black spruce treed bog: Moderately wet fibric organic Labrador tea shrubby bog: Wet fibric organic Open bog: Wet humic organic Tamarack treed fen: Wet fibric organic	17,075	8%
<b>Totals</b>		<b>227,367</b>	<b>100%</b>

### ***Initializing the Landscape***

The main inputs for LANDIS-II include spatial inputs such as an initial species and age cohort information, and an ecoregion map (Figure 6). All species and age cohort information were obtained from Saskatchewan's Forest Ecosystem Classification (FEC) vegetation data and the Saskatchewan Forest Vegetation Inventory (Saskatchewan Environment 2004). The ecoregions used in LANDIS are classified as ecosites according to the FEC, and were obtained from the Saskatchewan Ministry of Environment's Field Guide to the Ecosites of Saskatchewan's Provincial Forests (McLaughlan et al. 2010). Each ecosite was located within the Boreal Plain ecozone in Saskatchewan, and had homogenous soils, vegetation and site features. More details on each ecosite can be found in (McLaughlan et al. 2010). List of ecosites are found in Table 8 with a description of dominant vegetation, soil type, area on the landscape and its relative proportion.

Non-spatial parameters for LANDIS-II included species life history attributes, ANPP and SEP. Species life history attributes are used to simulate the succession pathways within the model. LANDIS was founded on the principle of vital attributes (Nobel and Slatyer 1980) which are unique life history characteristics of each species or functional groups. This information defines how a species will respond to disturbance and competition on the landscape. The parameters for the life history attributes table were estimated from literature (Viereck and Johnston 1990, OMNR 1997, Stewart et al. 1998, He and Mladenoff 1999, ArborVitae Environmental Services and KBM Forestry Consultants Inc. 2006, Ravenscroft et al. 2010).

### ***Species Life History Attributes***

The life history attributes required by LANDIS provide information regarding the propagation and death of species and their susceptibility to fire (ArborVitae Environmental Services and KBM Forestry Consultants Inc. 2006). Each parameter is interpreted below and Table 9 and 10 shows these data for each species. Black spruce on the landscape was divided into two different categories because upland and lowland black spruce exhibit different characteristics based on their location. Many parameters are estimates of the most common value found in literature; however care was taken to obtain values specifically for the study area when available.

**Table 9: List of life history attributes and their descriptions**

Life History Attribute	Description
Longevity	Longevity of the species in years. Individuals begin to die once the species has reached 80% of its longevity and complete age-related mortality occurs after this age
Maturity	Maturity age of the species in years. The species will begin to seed when this age is reached.
Shade Tolerance	Shade tolerance value; 1 = least tolerant; 5 = most tolerant
Fire Tolerance	Fire tolerance index value; 1 = least tolerant; 5 = most tolerant
Effective Seeding	Effective range of seeding distance in meters. Within this distance species have a 95% chance of seeding; beyond this distance the species have a 5% chance of seeding.
Max Seeding	Species maximum distance seeding range in meters
Veg. Prob	Probability of vegetative propagation following disturbance
Sprouting Age	Minimum age to be able to re-sprout (vegetative propagation)
Post Fire Regen	Indicates the type of post-fire, non-vegetative regeneration that can occur for each species

**Table 10: Life History Attributes**

Species	LNG	MTR	ST	FT	ED	MD	VP	SA <sub>Min</sub>	SA <sub>Max</sub>	PFR
Jack pine	141	10	1	3	20	60	0	0	0	serotiny
Tamarack	160	30	1	3	25	60	0	0	0	none
White spruce	211	30	3	2	30	200	0	0	0	none
Black spruce	180	30	4	3	79	150	0.9	20	100	none
lowland										
Black spruce	151	30	4	2	79	150	0.2	20	100	none
upland										
Balsam fir	150	30	5	1	25	160	0	0	0	none
Aspen	141	10	1	2	1000	5000	0.9	0	100	resprout
White birch	141	15	1	2	200	5000	0.5	0	70	resprout
Balsam poplar	141	10	1	2	1000	5000	0.9	0	100	resprout
Green alder	50	6	2	2	125	2600	0.9	0	50	resprout
Grass	5	1	1	1	100	10000	0.9	0	0	resprout

LNG, longevity (years); MTR, age of maturity (years); ST, shade tolerance (one is least tolerant and five is most tolerant); FT, fire tolerance (one is least tolerant and five is most tolerant); ED, effective seeding dispersal (m); MD, maximum seeding distance (m); VP, vegetative reproduction probability; SA<sub>Min</sub>, minimum sprouting age (years); SA<sub>Max</sub>, maximum sprouting age (years); PFR, post-fire regeneration. Green alder is actually composed of a combination of green alder and willow life history attributes which were averaged together to give general representation for shrub species.

Longevity is a key parameter and selecting the appropriate value is important. Longevity for most of the tree species were obtained from Saskatchewan's Provincial forestry lifespan values for each species (Bendzask 2011). Other sources included actual data on the ground, for example white spruce longevity was listed in the SK provincial forestry database to be around 170 years. However, some of the actual forest site data in the Island Forests had trees reaching over 200 years. Therefore, the value for white

spruce had to be adjusted to the maximum value found on the landscape. The same was done for balsam poplar and upland black spruce.

Shade tolerance is also an important parameter. Values for shade tolerance were taken from literature and estimated from the Silvics of North America (Burns and Honkala 1990) based on their description of shade tolerance. Species that were said to be very intolerant of shade were classified as a 1; intolerant = 2; intermediate = 3; tolerant = 4; very tolerant = 5. None of the species were especially fire tolerant; jack pine, tamarack and black spruce were classified as the most tolerant species to fire, while balsam fir was the most intolerant to fire. Vegetative reproduction is related to sprouting potential in hardwoods and layering in black spruce. Only jack pine was modeled as having serotinous cones, even though black spruce cones are sometimes considered semi-serotinous (ArborVitae Environmental Services and KBM Forestry Consultants Inc. 2006).

### ***Species Establishment Probabilities (SEP)***

Establishment probabilities for each species are assigned to each LANDIS designated ecoregion and initial SEPs are shown in Table 11. These SEP values were calculated from the actual forest inventory data and represent the proportion of area a species occupies within an ecoregion. SEP in LANDIS-II is the probability that one species is able to establish a cohort of small trees given that there is enough seeds in the site (LANDIS does not track number of seeds) within a specified time step (e.g. 5 years). Therefore, SEP will depend on species performance under specified climate and soil conditions, which may include many factors such as chilling requirement, drought tolerance, reproduction success and ground cover (Xu 2012). These initial SEPs were used to run the initial LANDIS simulations and recreate historical fire on the landscape. These values are replaced with SEPs from the PnET-II model to incorporate climate change variables into the scenario model runs. PnET-II estimates SEP in a more simplified way. It considers the water limitation, light limitation and CO<sub>2</sub> enrichment effect on photosynthesis. It simulates the effect of temperature on establishment based on the growing degree-days, but does not consider the environmental effects on reproduction, ground cover and understory shading on seed emergence and seedling establishment (Xu 2012). Therefore, estimation of SEP by PnET-II is likely to be higher than in the real world and there is an obvious need for the development of a more mechanistic model to simulate SEP by tracking seed number, flowering, chilling requirements and ground cover.

**Table 11: Initial Species Establishment Probabilities**

	BP2	BP3	BP4	BP6	BP7	BP9	BP11	BP12	BP13	BP14	BP15	BP16 BP17	BP19 - 23
Jack pine	1	1	1	0.01	0	0.3	0	1	0.05	0.5	0.01	0	0.1
Tamarack	0	0	0	0	0	0	0	0	0	0.1	0	0	1
White spruce	0	0.1	0.18	0.06	0.33	1	0.75	0.45	0.9	0.3	1	0.4	0
Black spruce	0	0	0	0	0	0	0	0	0	0	0	0	1
lowland Black spruce	0.024	0.1	0.12	0.01	0	0.3	0.01	0.8	0.05	1	0.4	0.01	0
upland Balsam fir	0	0	0.03	0.01	0.01	0.01	0.67	0	0.9	0.02	0.4	0.01	0
Aspen	0	0.25	0.63	0.98	1	0.67	0.5	0.1	0.7	0.3	0.6	1	0
White birch	0	0.006	0.09	0.08	0.46	0.4	1	0.15	0.6	0.1	0.6	0.01	0
Balsam poplar	0	0	0.03	0.01	0.01	0.15	0	0	0.4	0.1	1	1	0
Green alder	0.001	0.1	0	0.2	0.2	0.2	0.001	0.4	0	0.1	0	0.08	0.5

### **LANDIS-II Extensions**

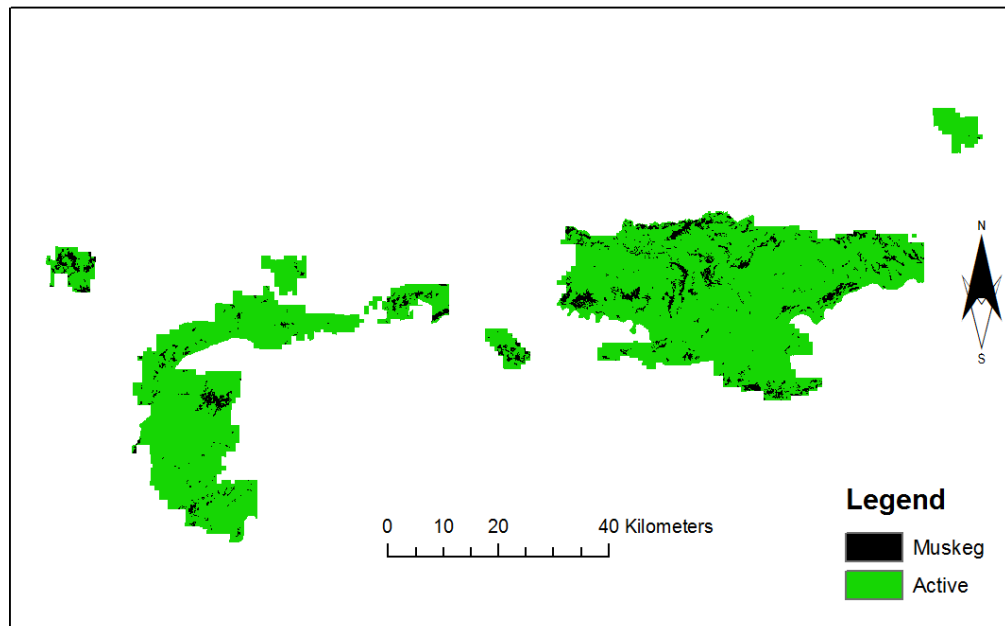
LANDIS-II consists of a core collection of libraries (Scheller and Domingo 2006) and a collection of optional extensions that represent the ecological processes of interest (Gustafson et al. 2010). The versatility of this model is the ability to choose which extensions to use to answer the research questions. There are three primary types of extensions that can be used with LANDIS-II: succession, disturbance and output extensions. The succession and disturbance extensions encapsulate the ecological knowledge represented in forested landscapes (Scheller et al. 2007). **Succession extensions** implement methods for cohort mortality, reproduction and growth (e.g. Biomass Succession extension). **Disturbance extensions** have individual time steps identified by the user, and they can be different from the successional extensions. There can be zero or more disturbances extensions for each scenario; examples include the Base Fire extension and the Biological Disturbance Agent extension. **Output extensions** read and aggregate the landscape data and create output text and raster maps (Scheller et al. 2007).

Two extensions were chosen to simulate the ecological processes that determine the composition and landscape structure of the study area under climate change: the Base Fire extension version 3.0.1 (Scheller and Domingo 2012) and the Biomass Succession extension version 3.0.1 (Scheller 2011).



### Base Fire Extension

The Base Fire module generates elliptical fires that are dependent upon the fire region established by the user. The fire region was set to encapsulate all of the Island Forests; input data for this extension are related to the fire return interval, fire size, and fire intensity. A fire in LANDIS results from the combination of stochastic ignition events and the risk of burning and spreading (Scheller and Mladenoff 2004). Fire regions for the study area are shown in Figure 8 below. There are two distinct fire areas on the map, Muskeg and Active fire regions. The Active fire region covers all of the forested area, but excludes bog and fen type zones. The Muskeg areas are composed of ecosites BP19 – BP23, and represent all the wetland areas in the region. The reason these two areas were separated on this landscape is because the wetland regions have a different fire return interval and can actually act as a natural barrier to fire. These areas needed to be distinguished from one another in order to realistically model fire ignition and spread on the landscape. Natural fire barriers are relevant in determining naturally patchy patterns of fires in any forest region and can include: riparian vegetation, wetland soils, lake margins and in some cases, ridge tops (WWF 2005).



**Figure 8: Fire Regions Map for the Island Forests, SK**

Historical fire data sets were used to parameterize the Base Fire Model. Historical fire data for the Island Forest region was first published by the Wildlife and Forestry branches of Saskatchewan Environment entitled the Forest Fire Chronology of Saskatchewan (SERM 2000, Canadian Council of Forest Ministers (CCFM) 2008). Other sources include the Canadian Forest Service and the Daily Forest Fire Information System (Natural Resources Canada 2012). These three sources were combined to give a historical fire record dating from 1959 to 2010 for the Island Forest region. Large historic fires are shown in Figures 9, and a summary of Historic Fire data found in Table 12.

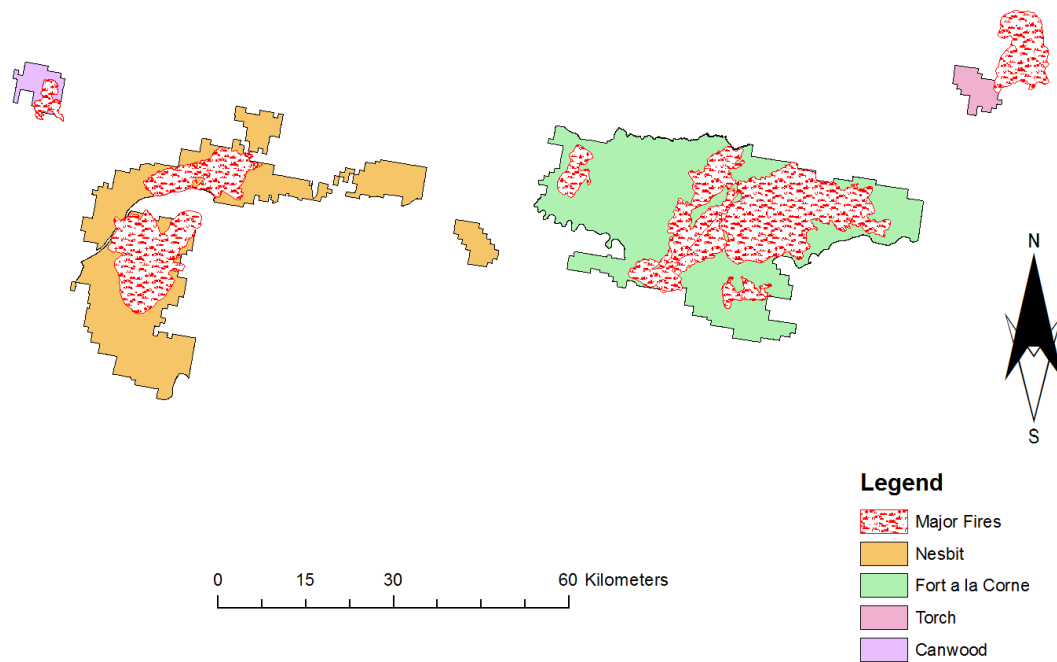
**Table 12: Summary of Historic Fire Data for the Island Forests region**

Fire Period	Total Area Burned (ha)	Avg Area Burned/Yr (ha)	No. Fires	Avg Fire Area (ha)	Fire return Interval (yr)
1959-2010	97,054	1,903	1,652	59	135

The total area burned by fire from 1959-2010 represents around 43% of the total region. From the historical record (SERM 2000, Natural Resources Canada 2012), eight major fires occurred in the region. Overall, the larger fires consumed 38% of the region with smaller fires being far more numerous and burning far less area. In the boreal forest, large fires are not numerically common, but cumulatively they typically burn much more area than the more abundant smaller fires (Figure 10) (Heinselman 1981, Hunter 1993, Thompson 2000). Fires that historically regenerated most of the boreal forest were likely larger than 400 ha, and frequently larger than 10,000 ha (Heinselman 1981). There are some challenges associated with using this historical fire record as a basis for estimating the fire regime in the Base Fire model. This includes trying to recreate the proper fire return interval while keeping a similar pattern of patch size frequency distribution and area burned by fires. There is a vast array of literature on boreal fire return times which describes fire cycles as “the number of years required to burn over an area equal to the whole area of the forest” (Van Wagner 1978). There is no single correct fire return time for any region (ArborVitae Environmental Services and KBM Forestry Consultants Inc. 2006) as large fluctuations have been observed in fire frequency and shifts between short and long fire cycles have been observed during the Holocene (Bergeron and Leduc 1998). The so called “natural” fire cycles in the boreal forest have been found to be as short as 20 years (Lynham and Stocks 1991) and as long as 500 years (Foster 1983). The nature of the Island Forest landscape also adds in another layer of difficulties when attempting to estimate fire return, as these forests are isolated from the larger boreal forest and from each other. This makes modeling fire on this landscape a bit more difficult as much of the literature and modeling programs assume a large area of continuous forest cover.

**Table 13: Summary of large fires that occurred from 1959-2010 in the Island Forests**

Year	Fire Name	Area burned (ha)
1967	Steep Hill	15,392
1989	Henderson	10,913
1989	North Cabin	18,067
1995	English	28,400
2000	Beaver	2,119
2001	Arrow	2,400
2002	Crutwell	8,445
<b>Total</b>		<b>85,736</b>



**Figure 9: Large fires showing areas burned across the Island Forests Landscape (1959-2010) (SERM 2000)**



**Figure 10: Historical Fire histogram for the Island Forests (SERM 2000)**

### **Biomass module**

The Biomass Succession extension calculates competition among cohorts, the increase of living biomass in cohorts of each tree species, and the gain and loss of woody and non-woody dead biomass using life history attributes. It calculates ecosystem process rates and the quantity of aboveground living biomass ( $\text{g/m}^2$ ) for each tree species-age cohort (Scheller and Mladenoff 2004). A single site can have >10 species-age cohorts, each of which has an associated living biomass value. The Biomass extension interacts with all of the disturbance modules, allowing landscape processes to interact with each other through their effects on biomass by calculating three process rates: aboveground net primary productivity (ANPP), aboveground mortality, and woody biomass decomposition (Scheller and Mladenoff 2004). Mortality is the rate of biomass transferred from the living biomass to the dead biomass pool and includes the loss of branches, tree death and loss of leaves. This module operates at an annual time step. Maximum values for ANPP ( $\text{ANPP}_{\text{MAX}}$ ) were calculated for each ecoregion and species, and are shown in Table 14. Calculations were done using Canada's national tree aboveground biomass equations (Lambert et al. 2005). These equations used the following format:

$$(1) \quad y = a D^b$$

Where  $y$  is equal to the oven dry weight of above ground biomass component of tree in kilograms;  $D$  is equal to the tree's diameter at breast height in centimeters; and  $a$  and  $b$  are parameters that are different for each species. The species specific parameters were obtained from Lambert et al. (2005) and diameter at breast height (DBH) was obtained for each LANDIS ecoregion from the Field guide to the Ecosites of Saskatchewan's Provincial Forests (McLaughlan et al. 2010). The field guide describes DBH as: 1.3 meters in height and "it is the average diameter associated with each species (by ecosites) of all the trees in the plots with a diameter at breast height of greater than 7.5 cm (McLaughlan et al. 2010).  $\text{ANPP}_{\text{MAX}}$  was used to constrain the model by putting a limit for the maximum allowable aboveground biomass for the species in each of the ecoregions.

**Table 14: Initial Biomass inputs for each species and ecoregion (g/m<sup>2</sup>)**

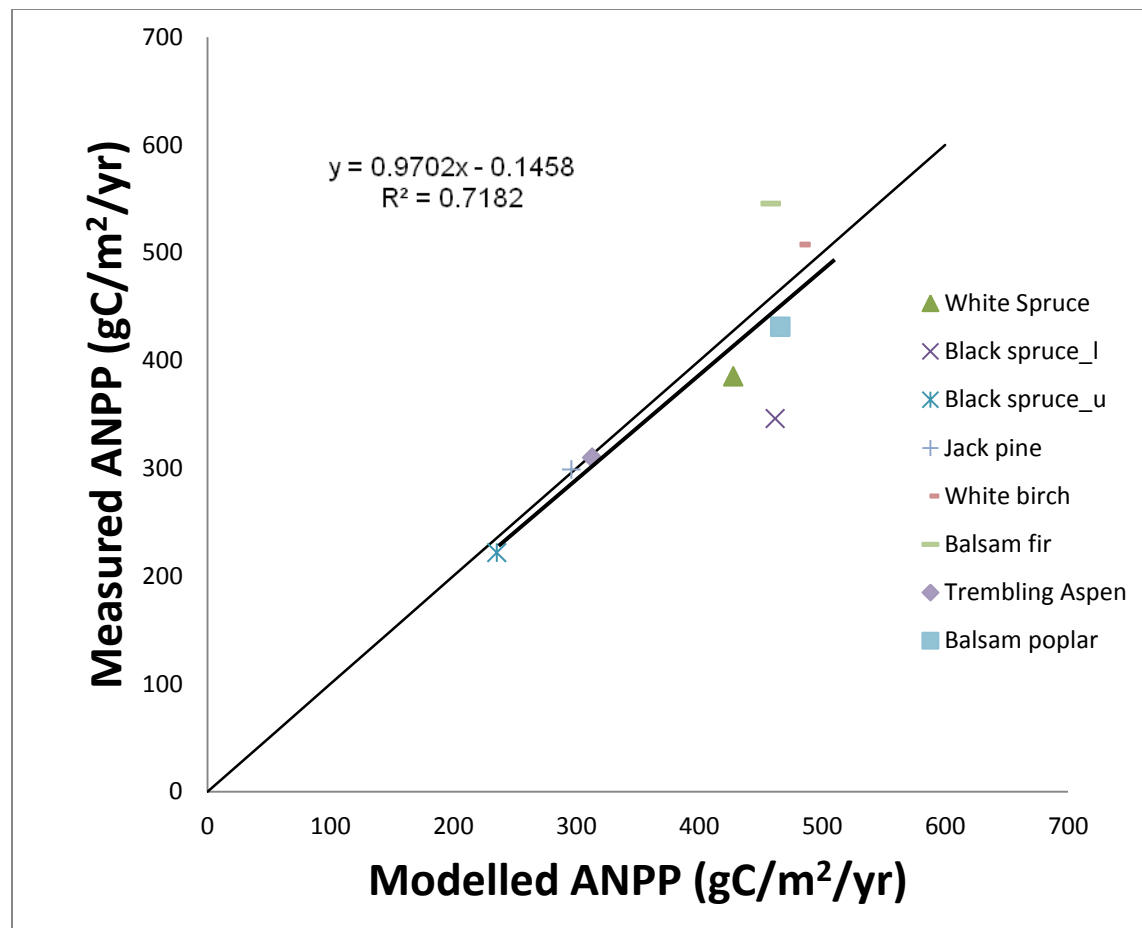
	Ecoregions	BP02	BP03	BP04	BP06	BP07	BP09	BP11	BP12	BP13	BP14	BP15	BP1617	BP1923
<b>Species</b>	<b>pinubank</b>	75,482	107,413	88,511	0	24	708	112	102,647	0	45,372	27,877	0	8,908
	<b>abiebals</b>	0	0	4,188	16,867	0.00	4,435	32,349	0.00	31,870	1,895	4,466	30,820	0
	<b>betupapy</b>	0	9,289	9,848	8,985	11,451	17,602	17,602	4,677	51,099	12,764	14,394	79,336	0
	<b>larilari</b>	0	0	0	5,441	0	0	0	0	0	17,610	0	0	15,699
	<b>piceglau</b>	0	10,941	19,152	35,823	18,825	13,641	48,834	37,756	108,707	50,901	15,986	25,115	0
	<b>picemariu</b>	0	5,713	9,779	12,110	9,909	19,077	50,806	28,094	73,510	71,702	36,102	0	0
	<b>picemaryl</b>	0	0	0	0	0	0	0	0	0	0	0	5,574	19,104
	<b>popubals</b>	0	0	37,702	10,369	62,685	28,529	19,291	1,461	60,636	28,389	43,925	145,184	0
	<b>poputrem</b>	0	4,997	28,409	154,435	92,468	45,107	27,789	13,616	77,380	59,066	12,766	72,067	0
	<b>alnuviri</b>	0	0	0	0	0	0	20,712	0	0	0	0	69,934	57,093

## 4. Model Calibration and Validation

### Validating the PnET-II Model

The PnET-II model results for ANPP were compared with actual measured ANPP values (Figure 11) to ensure that the PnET model was able to accurately represent forest ecosystem function for this region. ANPP measurements were not available for the Island Forest region, so field measurements were obtained from the closest location possible found in literature (Gower et al. 1997, Lavigne and Ryan 1997, Gower et al. 2000, Gower et al. 2001, Li et al. 2002, Bond-Lamberty et al. 2004, Bernier et al. 2007). All of the model outputs were within range of observed values and this confirmed that the PnET model was calibrated properly and able to closely predict ANPP for the Island Forest region. Measured ANPP versus modeled ANPP gave an R-squared value of 0.72, which shows that the correlation between the two variables is high and PnET-II is producing reasonably accurate output. Lowland black spruce and balsam fir had the largest discrepancies, and if these two species are removed from the calculation, the R-squared value is substantially improved ( $R^2 = 0.94$ ). Lowland black spruce may have more inaccurate values because it was more difficult to find parameters specifically for wetland species. Therefore, the only difference in the PnET-II parameters between the lowland and upland black spruce was the amount of water available for growth and this may be the reason PnET-II was unable to produce more accurate values for this vegetation type. If more accurate parameters could be obtained, the model results would probably improve. Measured ANPP was difficult to find for balsam fir near the study location. Therefore, measured ANPP was averaged for balsam fir trees in New Brunswick and across Canadian Fluxnet sites. This may have caused the large discrepancy in the measured versus predicted ANPP values for balsam fir, as ANPP can vary quite extensively across Canada and the measured value may not be an accurate reflection of if balsam fir trees in Saskatchewan. However, balsam fir is not an important component of the Island Forest vegetation, so this was not considered a significant problem.

PnET-II is able to model the CO<sub>2</sub> effect on stomata conductance and photosynthesis (Ollinger et al. 2002, Xu et al. 2009). These two options in the model allow the user to examine the effects of CO<sub>2</sub> fertilization and increased water-use efficiency on tree species. However, PnET-II tended to greatly overestimate ANPP for species in this region when either of these two effects was activated and were not implemented in the simulation runs.



**Figure 11: Comparison of modelled and measured above-ground ANPP of major tree species in the Island Forest. Measured values are from literature sources, not measured in the study site.**

## Calibrating the LANDIS Successional Model

The successional mechanisms in LANDIS-II were calibrated by examining the interacting effects of species on the landscape with no disturbances present. This isolates the successional dynamics in the model allowing the modeler to determine if the species' successional behavior is working properly on the landscape (i.e.; the life history attributes are functioning appropriately).

Figure 12 shows the species presence on the landscape over the simulation time period, with fire turned off. As expected, most species decline within the first 140-150 years due to natural mortality (their maximum longevity has been reached). One exception was white spruce, which due to its longer longevity (211 years) took a much longer time to decline. Jack pine, larch and white birch, which are early succession species, almost disappear after 140 years. These species require landscape disturbances to allow them to reestablish, as they require considerable light for germination and growth. Jack pine also requires fire to release its seeds from its serotinous cones; therefore, it is not a surprise that its presence drops drastically on the landscape. Trembling aspen, white spruce and upland black spruce

become the dominant species on the landscape at the end of the simulation time period in the absence of fire. Both white spruce and upland black spruce are shade-tolerant species which allows them to reestablish after 140-200 years. Black spruce also has the ability to reproduce by layering which may have given the upland variety the ability to reestablish.

Figure 13 depicts species presence on the landscape with historical fire. Similar to the landscape with no fire, species decline over time as their natural mortality age is reached. Larch and white birch, which are early successional species, disappear after 140 years. Jack pine remains on the landscape now that fire is present and its seeds can be successfully released from their cones after fire. Trembling aspen and jack pine become the most dominant species on the landscape at the end of the simulation period. This shows that the model is recreating successional and fire dynamics on the landscape properly, as these are the two species that are currently the most prominent in the Island Forest regions.

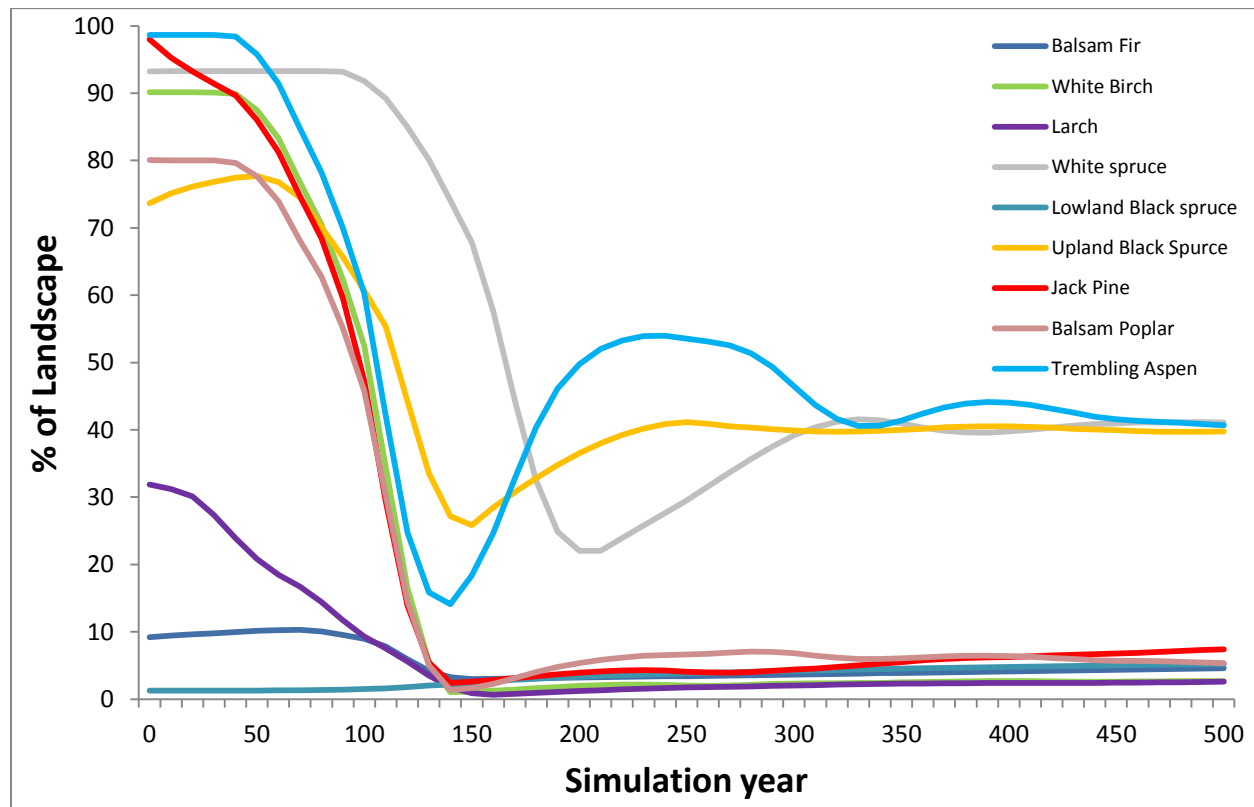
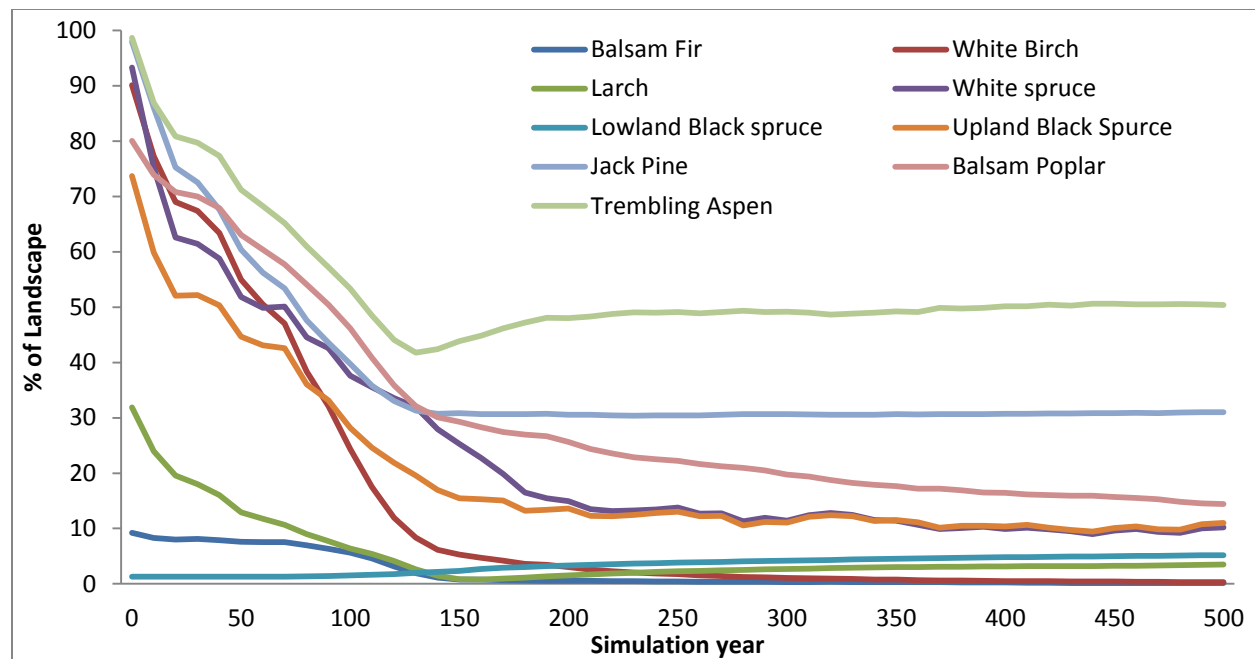


Figure 12: Simulated species presence over time in the Island Forests with fire absent on landscape



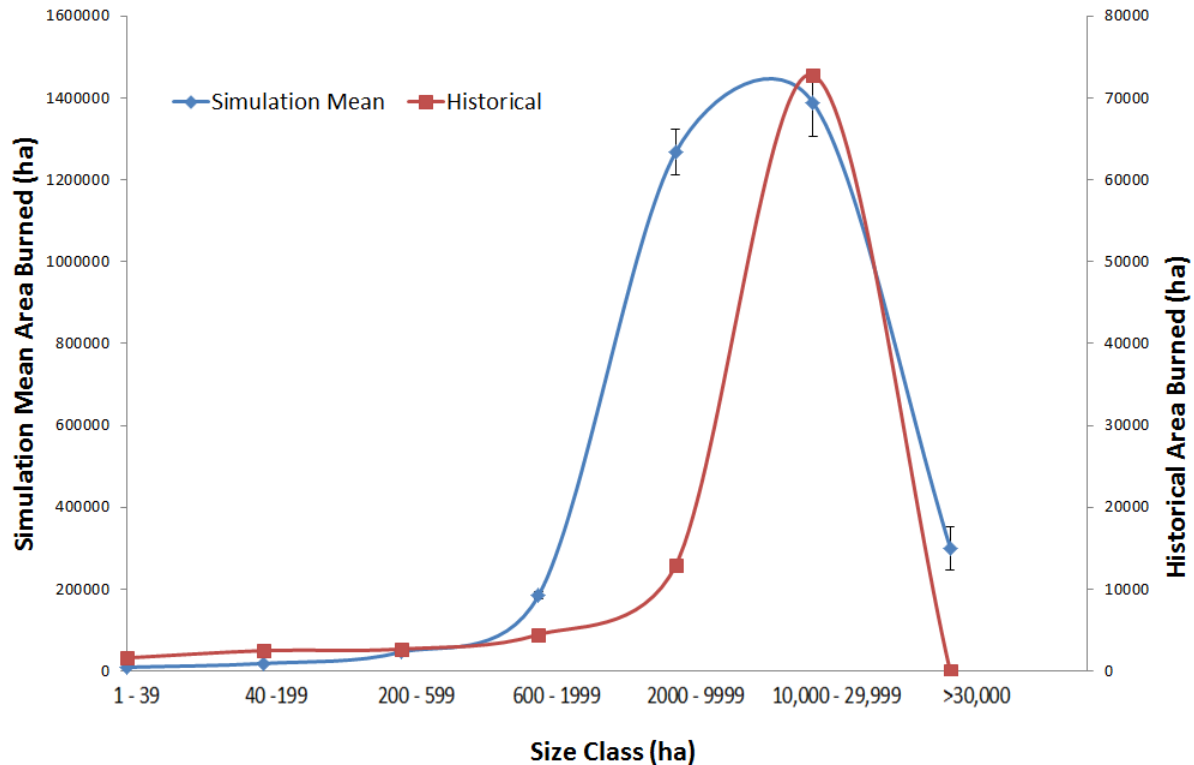


**Figure 13: Simulated species presence over time in the Island Forests with Fire on the landscape**

### Calibrating the Base Fire Model

The fire regime for the Island Forests region was established by numerous runs and validating each output using the historical data set. The goal was to be able to recreate the historical fire return interval, areas burned, and patch size frequency distribution using historical fire data and climate data. Figure 14 shows the fire histogram for the historical fire data which was used to compare all the results from the model runs. The run that was able match these constraints best was chosen to simulate fire on the landscape. This step turned out to be very time consuming, and involved fifty trial runs to obtain a proper calibration. In all calibration runs, the random-number generator internal to LANDIS was initialized to a constant number to eliminate differences in outcome due to the stochastic nature of the LANDIS modeling environment (ArborVitae Environmental Services and KBM Forestry Consultants Inc. 2006).

The modeled fire was done over a 500 year simulation while the historical fire was based on 50 years of records. The 500 year simulation was used to make sure that the long-term mean was similar to the historical record. The modeled fire return was 130 years, which is close to the historical target for this region, 135 years. It does produce some fires above 10,000 ha, and slightly more fires in the larger patch sizes, but it seems reasonable to assume that larger fires will occur over a 500 year time period. The annual burn rate for the modeled fire was 1617 ha, where the historical burn rate was 1554, a difference of only 0.7%. Overall, the base fire model produced satisfactory data for this region given the limited amount of historical fire data that was available.



**Figure 14: Fire Histograms showing historical fire versus modeled fire on the Island Forest landscape using the LANDIS base fire model.** The y-axis for both graphs is different because they are based on 500 years of simulated fire and 50 years of historical fire. The importance shown in these graphs is in the shape of the curve depicting fire size classes. Error bars show standard deviation among the five simulations

### Validating the Biomass Model

The biomass model was run for a ten year period in order to examine whether the output was comparable to actual biomass ( $\text{g/m}^2$ ) on the landscape. Five simulation runs were averaged together and gave a value of  $5959 \pm 228 \text{ g/m}^2$  of live biomass for the entire region during the ten year simulation (2000-2010). During these simulations, fire was present on the landscape based on historical fire values to give the most accurate estimate of actual biomass.

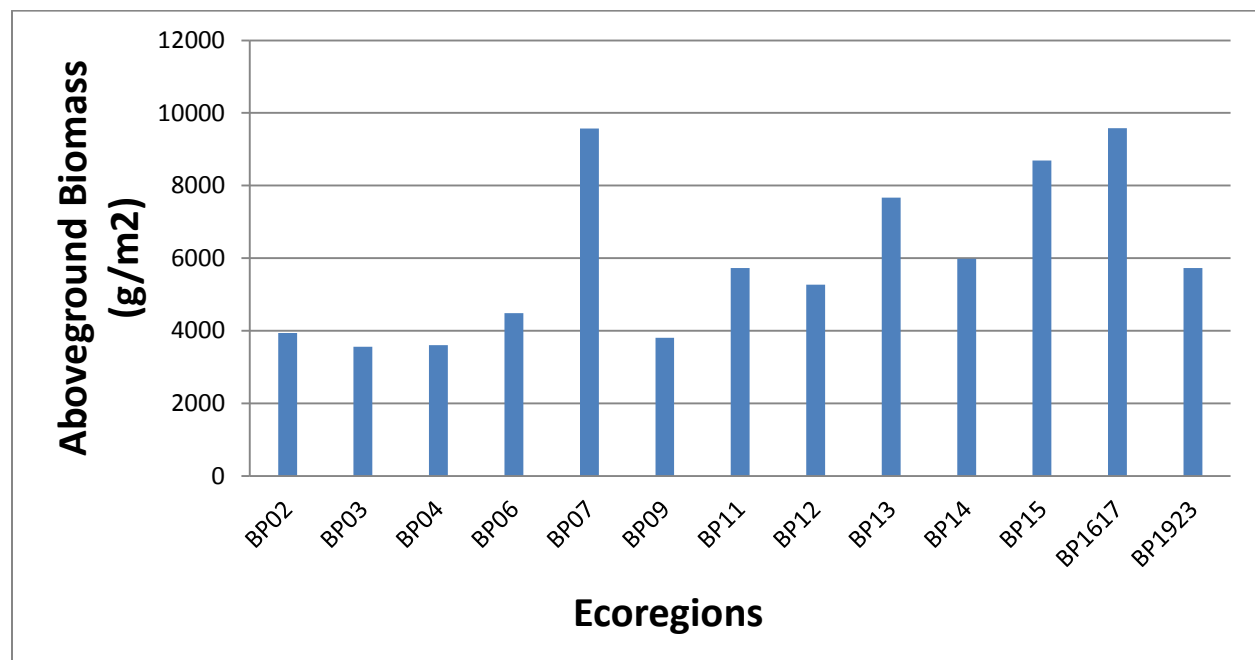
Actual biomass values were obtained from literature and compared to simulated biomass from the LANDIS-II model (Table 15). Actual biomass ranged from 3140 to  $7300 \text{ g/m}^2$  for boreal forest estimates in Canada. The modeled value falls in the middle of this range obtained from literature and therefore, was considered to be acceptable. Remarkably, the average modeled biomass is very close the biomass value for the BOREAS Southern Study Area (SSA) in Saskatchewan, which is the closest region to the study area (see highlighted section in Table 15).

**Table 15: Literature data for aboveground biomass ( $\text{g/m}^2$ ) compared with simulated biomass for the total Island Forest landscape over a ten year period (2000-2010)**

Modelled Biomass ( $\text{g/m}^2$ )	Actual Measurements of Biomass ( $\text{g/m}^2$ )	Location	Source
5959 $\pm$ 228	3140-5190	North American Boreal Forest	(Botkin and Simpson 1990)
	7300	BOREAS SSA	(Ranson et al. 1997)
	7017	Canada Boreal Forest (1989-1990)	(Myneni et al. 2001)
	5904	Saskatchewan (BOREAS SSA)	(Gower et al. 2001)

Results from the biomass model validation are also shown for each ecoregion in Figure 15. Ecoregions which are lower in productivity such as BP02, BP03, and BP04 which are jack pine stands on sandy soils show lower biomass. Likewise, the more productive sites such as trembling aspen, white spruce, and balsam poplar stands have higher biomass.

A study by Goetz and Prince (1999) modelled biomass for trembling aspen and lowland black spruce stands in Minnesota, finding values of 11829 and 7396  $\text{g/m}^2$ , respectively. These values are larger than the modelled values in this study where the Island Forest aspen stands showed an average biomass of 9571  $\text{g/m}^2$  for aspen and 5731  $\text{g/m}^2$  for lowland black spruce. This seems reasonable as the Island Forests are located in a dry region with poorer soils, and this would account for the lower productivity relative to the stands in Minnesota.



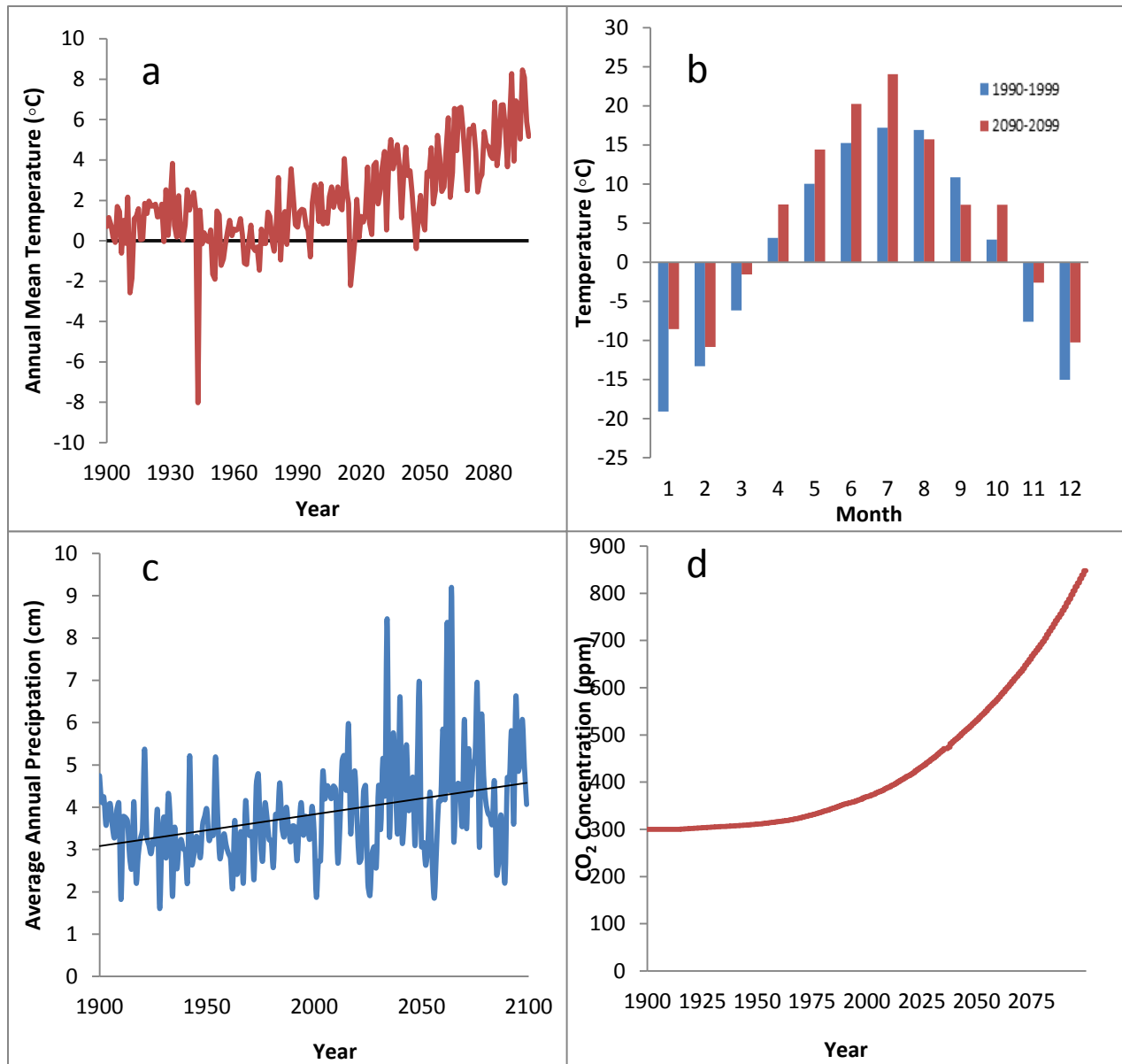
**Figure 15: Simulated aboveground biomass ( $\text{g/m}^2$ ) for each ecoregion in the Island Forests over a 10 year time period (2000-2010)**

## 5. Climate Change Scenarios

In order to produce a robust assessment of potential effects of climate change for a region, a climate change scenario approach is used to predict future temperature and precipitation. At least three to five scenarios are recommended in climate modeling because it gives a range of future climate variability that is most likely to incorporate the actual future climate. The original plan for this paper was to use five different climate scenarios and examine their range of variables and potential impacts on climate change, see Box 1 for complete details. However, due to time limitations, only one scenario was used for the modeling analysis. The CRCM version 4.2.3 was used to run a single climate change scenario for the Island Forests region. This model is driven by CGCM3, following IPCC “SRES A2” GHG scenario over the North-American domain with a 45-km horizontal grid-size. The source of the data for the CRCM is generated and supplied by the Ouranos Climate Simulation Team via the Canadian Center for Climate Modeling and Analysis data distribution web page (Music and Caya 2007). The A2 emission scenario used in this analysis is considered to be one of the more aggressive emission scenarios. 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. Atmospheric CO<sub>2</sub> concentrations in this scenario are projected to reach 856 ppm by 2100, or approximately triple that of preindustrial levels.

According to the CRCM4.2.3 projections, there is about a 6°C increase in average annual temperature from the early 1900s to the end of the century (Figure 16a). Winter temperatures increase quite substantially with the highest deviation in temperature occurring in January (10°C), summer temperatures increase in all months, except August and September (Figure 16b). This means that during the growing season trees will be subjected to higher temperatures, which may or may not cause an increase in productivity depending on site conditions. Wetter sites with sufficient moisture may see an increase in productivity. However, in dry regions like the Island Forests, an increase in temperature is likely to cause a decrease in productivity due to drought stress (Hogg and Bernier 2005). Species that are better adapted to dealing with drought will likely have a better chance of surviving under future conditions. Although temperatures increase substantially in some of the winter months, this will not have much effect on tree photosynthesis except for in very warm winters.

According to the CRCM4.2.3-A2, precipitation does increase under climate change; however, these changes are not substantial and show high amounts of annual variation in the future (Figure 16c). It is well known that climate models are better at predicting temperature increases than precipitation, therefore, it is important to realize that there is high uncertainty associated with future estimates of precipitation. However, if the model turns out to be correct, it is likely that the few centimeters of increased water on this landscape will not be enough to compensate for the overall temperature increases which will bring about higher evaporation and transpiration. Therefore, higher temperatures and a small increase in overall precipitation on a marginal landscape like the Island Forests are likely to cause decreases in overall productivity due to moisture stress.



**Figure 16: Climate change inputs for PnET-II and LANDIS** (a) annual mean temperatures (°C); (b) monthly mean temperature differences between the historic 1990-1999 climate and the predicted 2090-2099 climate; (c) annual precipitation (cm); (d) annual mean CO<sub>2</sub> concentration (ppm). Data from CRCM4.2-A2

## Climate Change and Fire

Fire activity plays a major role in the life cycle of Canada's forests and research into the potential impacts of climate change on fire activity in Canada has been ongoing since the early 1990s (Flannigan and Van Wagner 1991, Stocks 1993, Wotton and Flannigan 1993, Flannigan et al. 1998, Flannigan et al. 2000, Flannigan et al. 2009). Early work concentrated on the impacts of climate change on overall fire season severity using output from GCMs and later, scenarios generated by Regional Climate Models showed that while there were some strong regional differences in Canada, overall fire seasons would increase in both length and severity (Wotton et al. 2010).

Some of the recent climate predictions and its effects on Canadian boreal forest fire can be found in Table 16. Results from Balshi et al. (2008) were used to adjust the historical fire values in the base fire model and show the potential effect of an increase of 1.2x area burned by 2050, and an increase of 5.5x burned area by 2100, relative to 1991-2000. These values were chosen because Balshi et al. (2008) used the Canadian climate model, CGCM2 with the A2 emission scenario which was close to the climate data that was run in the rest of the LANDIS model.

**Table 16: Recent studies showing predictions on how climate change will affect fire in the Canadian Boreal Forest**

Climate Change Model	Location	Predicted Change	Time period	Reference
Linear multiplier	Saskatchewan	Fire increase by 4x	2100	Metsaranta et al., 2010
CGCM1	Canada	Increased fire occurrence by 25%	2030	Wotton et al., 2010
CGCM1	Saskatchewan	8% increase in total annual fire occurrence rate	2030	Wotton et al., 2010
CGCM1	Canada	Increased fire occurrence by 75%	2100	Wotton et al., 2010
CGCM1	Saskatchewan	22% increase in total annual fire occurrence rate	2100	Wotton et al., 2010
HADCM3	Canada	Increase fire occurrence by 82%	2100	Wotton et al., 2010
HADCM3	Saskatchewan	Increase fire occurrence by 140%	2100	Wotton et al., 2010
CGCM2 (A2 emission scenario)	Western Canada	Average <b>area burned</b> per decade will double	2041-2050	Balshi et al., 2008
CGCM2 (A2 emission scenario)	Western Canada	<b>Area burned</b> increases on the order of 1.2x per decade	2050-2100	Balshi et al., 2008
CGCM2 (A2 emission scenario)	Western Canada	Relative to 1991-2000 <b>area burned</b> increase by 5.5x	2100	Balshi et al., 2008
CGCM2 (A2 emission scenario)	Western Canada	<b>Fire Return Interval</b> decrease by 40%	2070-2100	Balshi et al., 2008

## 6. Results and Discussion

Once the model was calibrated properly, a set of 3 LANDIS-II simulations were run over a 500 year simulation horizon, representing the period from 2000 to 2500. Uncertainty is particularly high after the first 100 years of simulation, because at this point the original forest becomes largely removed by disturbance and age-related mortality (Xu et al. 2009). However, the modeling scenarios were run for an additional 400 years after the CGCM4.2 climate profile in order to reach steady-state conditions and examine forest dynamics in the altered climate (He and Mladenoff 1999). With model simulations it is important to run the model for a long time period, such as 500 years, to allow for realistic representation of the ecological processes on the landscape. This allows the creation of realistic patch size and age-class distributions to be generated. These simulations were average together to produce outputs of: species presence, age classes, fire probability, aboveground NPP, changes in forest landscape composition and biomass under climate change. All replications were performed using random number seeds, and they were not tested for significant differences.

### Fire Dynamics

Fire simulations were run on the landscape for 500 years. As discussed in section 5, future fire predictions were based on findings by Bashi et al., 2008 which showed an increase in area burned by 1.2x by 2050 and 5.5x by 2100. Using this data, the fire model had to be recalibrated for each time period to reflect this change in fire. Table 17 shows the actual results from this modeling exercise. During the fire model calibration for the 2050s and 2100s, fire spread values were changed slightly from values obtained by Bashi et al., 2008, but remain within the range predicted. Area burned by 2050 was increased to 2x historical value, while the area burned by 2100 was increased to 3x historical rates. The 5.5x increase in area burned for the 2100s, had to be decreased because at the rate of 5.5x the entire Island Forests region was burned entirely. At this burn rate, the maximum fire size for the Island Forests (historical max fire size x 5.5) reached 220,000 ha. The entire Island Forests region, encompassing all 4 forests, has a total of 226,423 ha. Therefore, under this climate change regime a single fire has the potential to burn the entire forest area, leaving nothing behind. Given these values, one can likely assume that under a climate change regime of 5.5x historical burn rates, the Island Forests could potentially be entirely removed from the landscape.

During the calibration run for the 2100s, burn rates could not even reach the predicted levels of 5.5x the historical. For example, the largest amount of area burned in one modeling simulation was around 2 million ha (half as much predicted under the 5.5x burn rate). There was just not enough forest to burn. Since these results were unable to be actually modeled at the high rate of 5.5x historical values, the burn rate was reduced to 3x the historical value. This way increased fire on the landscape can still be modeled and changes in the forest landscape can be analyzed.

The difficulties when trying to model fire on this landscape under climate change was largely attributed to the small area which the Island Forests represent and the fact that burn rates for future climates were actually calculated for a much larger area, the entire western boreal forest of Canada. This may have caused some of the difficulties that were encountered in the modeling process. The Island Forests are obviously quite different in landscape structure relative to the boreal forest. The boreal forest is a

continuous forested region, while the Island Forests are broken up into isolated forest areas and separated by agricultural land. The size of the western boreal forest area is vast (millions of ha), whereas the Island Forests are minuscule in comparison. Along with different soils and ecoregions, the Island Forest's fire regimes are unique to this area and will likely respond to climate change differently than the larger boreal region. However, data describing how fire dynamics in the Island Forests might change under future climate scenarios is lacking and therefore the aim of this study was just to show how increases in fire under climate change will affect this landscape. Although the actual rates of fire change on the landscape are unknown, by showing an increase of 2x and 3x historical burn rates some basic conclusions can be drawn on how climate change may affect the Island Forests in the future. The results from this analysis are described below.

**Table 17: Comparison of historical, 2050s and 2100s fire spread values for the study region**

	Historical Actual	Historical Obtained	2050s 2x historical	2050s Obtained	2100s 5.5x historical	2100s 3x historical	2100s Obtained for 3x historical
<b>Fire Return (years)</b>	135	130	Between 130 and 80	108	85	85	89
<b>Max fire size (ha)</b>	40,000	40,000	80,000	80,000	220,000	120,000	120,000
<b>Min Fire Size (ha)</b>	25	25	50	50	75	75	75
<b>Average Fire size (ha)</b>	10,000	10,000	20,000	20,000	30,000	30,000	30,000
<b>Area Burned (ha)</b>	776,538	796,948	931,846	974,485	4,270,959	1,164,807	1,178,200
<b>Area Burned per year (ha/yr)</b>	1554	1617	1864	1949	8542	2,330	2,356

As shown in Table 17, the Base Fire model was able to closely reproduce area burned by fire for the historical, 2050s, and 2100s. Actual historical area burned was 776,538 ha and the model average produced a value of 796,948 ha, a difference of 0.03. Similar results were obtained for the 2050s, (2x historical value equaling 931,846 ha and the modeled value of 974,485 ha), a difference of 0.05, and 2100s, (historical 1,164,807 ha vs. modeled 1,178,200 ha) a difference of 0.01. Therefore, if climate change causes fires to be more frequent and burn twice and three times as much as current fire on the landscape annual burn rate per year could increase from 1155 ha/year to 2300 ha/year. Overall, this would be an increase in overall area burned over the simulation period of 388,269 ha, an area larger than the entire Island Forest region. How this has affected the forest composition and vegetation dynamics will be described below.

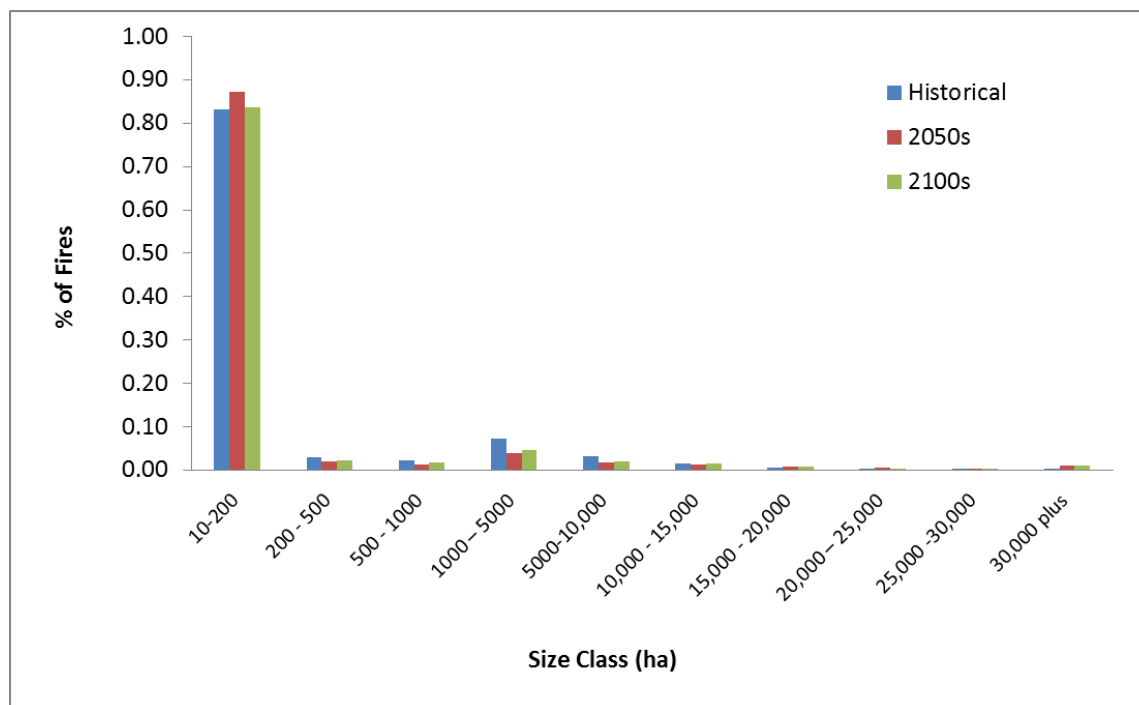
### **Fire Size Class Frequency**

The simulated frequency of burns by fire size class in the Island Forests is shown in Figure 17 for each modeled time period. All fire size class frequencies follow the historical pattern of fire, with more frequent small fires and less frequent larger fires. This shows that the model is creating fires on the

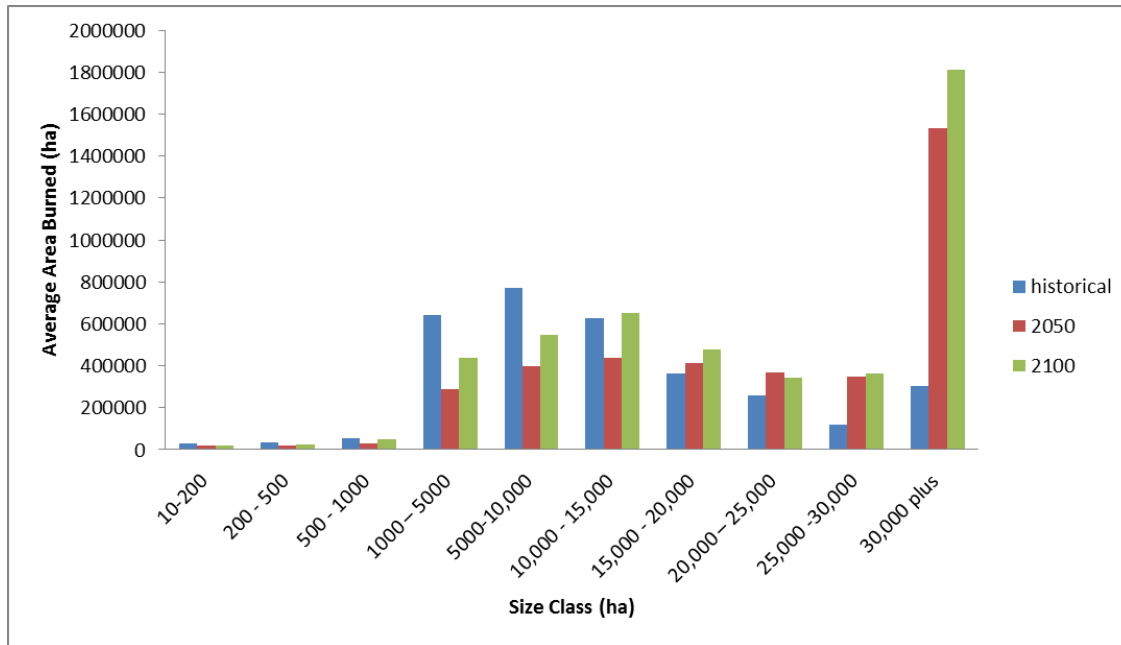


landscape that exhibit natural fire regimes, with infrequent large fires and the vast majority of fires occurring in the smallest class size. The percentage of smaller fires (10-200 size) rises under climate change, especially in the 2050s. The same can be seen for the larger sized fires, showing that the model was able to create a future climate with more frequent larger fires. Some of the mid-sized fire classes actually show decreases in fire frequency, which is probably due to the increase of fires in the other size classes. Therefore, this model shows that future fires have a larger probability of becoming greater in size and extent of area burned.

Although small fires are the most common, infrequent large fires account for the vast majority of area burned. Figure 18 shows that the larger fire size classes constitute greater area burned relative to smaller fires. The historical fire regime shows larger area burned for the midsized fire classes, with a peak occurring in the 5000 to 10,000 fire class, and area burned decreases sequentially after this. The 2050s and 2100s show a slightly different arrangement of area burned, with the highest peak occurring in the 30,000 plus fire size class. This shows that under future climate change, the largest fire classes will indeed produce the largest area burned. Whereas, under historical fire regimes area burned was largest in the 1000 to 15,000 fire classes. These differences are observed because very large fires such as 30,000 or more were very rare historically. However, under climate change larger fires will become more frequent causing larger amounts of areas to be burned across the Island Forest. Another observation that can be made from Figure 18 is that average area burned is substantially higher in the 30,000 plus fire size classes. Overall, the 2100s have a higher area burned relative to the 2050s for the majority of fire size classes. This shows that the model was able to create a higher percentage of fires and an increased area burned under future conditions.



**Figure 17: Fire size class frequency modeled under historical and future conditions (2050s and 2100s)**



**Figure 18: Average area burned modeled under historical and future conditions (2050s and 2100s)**

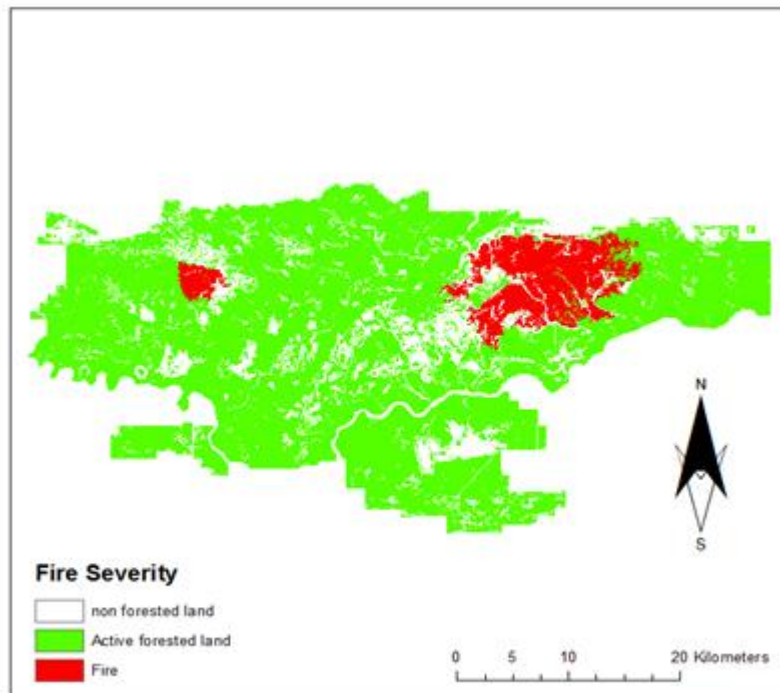
Increases in fire can have drastic consequences on the vegetation structure and functioning. Fire is the dominant disturbance that drives ecosystem structure and function in the boreal forest North America (Weber and Flannigan 1997). Sites opened by disturbance allow regeneration of vegetation, thereby often maintaining vegetation composition and successional cycles. Depending on the post disturbance environment, disturbance can also accelerate changes in vegetation composition, possibly resulting in different vegetation dynamics and altered biodiversity (Thonicke et al. 2001). The current vegetation communities have adapted to the current fire regime, which has allowed them to survive and reestablish on the landscape once a disturbance has occurred. If fire increases in a region, it can drastically alter community dynamics, such as: regeneration, competition, reestablishment and survivability. This season of burning and the time between reoccurring fires determine the plant species composition in most ecosystems (Thonicke et al. 2001). For example, black spruce, exhibits slow growth, taking several decades to reach reproductive maturity. Historical fire cycles allow for black spruce to accumulate enough viable seeds for replacement after fire. Because of the long period black spruce require to become productively mature, an increase in fire activity may interrupt the cycle of post fire self-replacement for this dominant boreal conifer (Brown 2010). The effects of increased fire on the Island Forests will be described in the following sections.

### ***Landscape Disturbance Pattern***

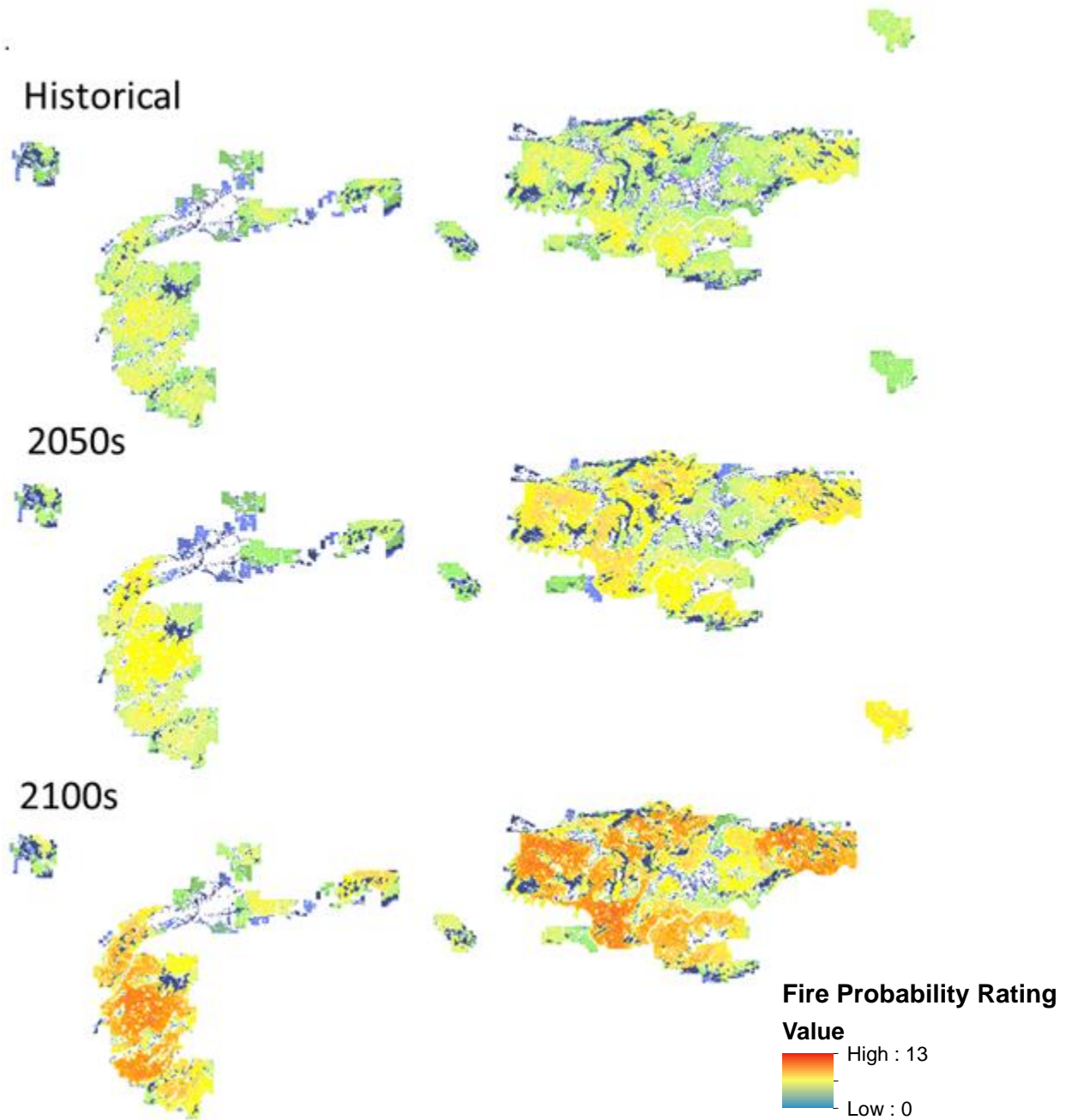
Annual fire disturbance patches are spatially varied across the landscape for each modeling period. Figure 19 below, shows the fire disturbance for a single year in the Fort à la Corne Island Forest. All 500 fire disturbance layers for each replication were combined to provide a complete spatial layer showing areas that have a high likelihood of burning. The layers shown in Figure 20 were calculated by summing the total number of times each cell (site) was disturbed over the simulation period for all replications.

The data represents a total disturbance over a 1500 (500 year simulation x three replicates) simulation period. The areas represented with the blue color show areas of lower burn probability, and the orange to red colors show areas with higher burn probability in the Island Forests. The fire severity rating or burn probability increases from the historical to the 2100s for most areas on the landscape (Figure 20).

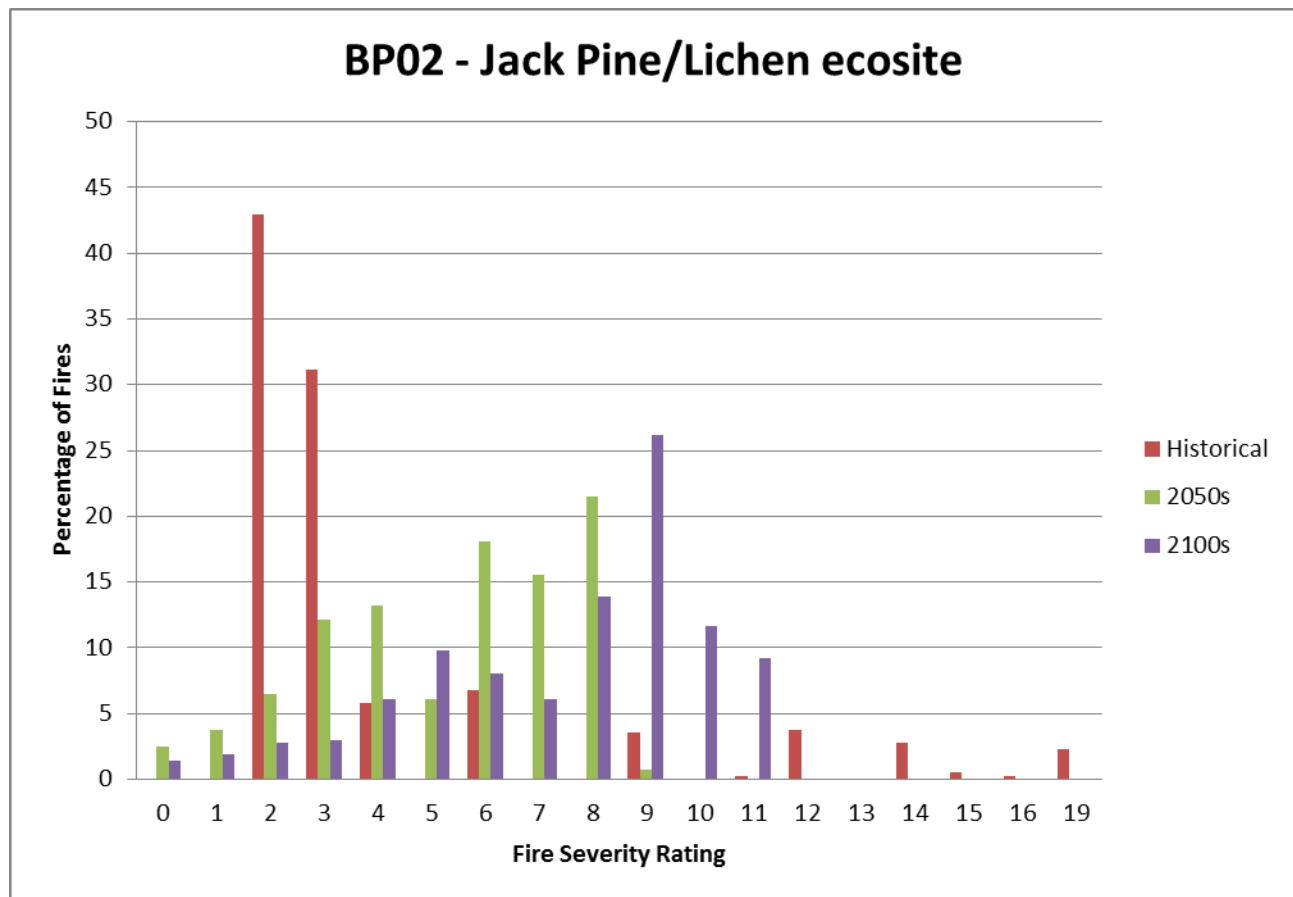
Increases in fire severities occurred in the 2050s to the 2100s simulation, for all ecoregions. Historical simulations had more random fire severities, but the majority occurred in the lower range (example Figure 21). For the majority of the jack pine and trembling aspen dominated ecoregions, fire severity increased over each sequential simulation period. However, not all ecoregions had increases in fire severities. White spruce, balsam fir, and balsam poplar ecoregions all showed a decrease in fire severity over simulation time (historical to 2100s), which higher severities occurring in the historical period.



**Figure 19: Modelled fire disturbance (red zones) for a single year in the Fort a la Corne Island Forest**



**Figure 20: Maps showing modelled fire probabilities for the Saskatchewan Island Forests under Historical and future climate conditions.**



**Figure 21: Percentage of fires by severity rating for the BP02 ecosite under historical, 2050s, and 2100s simulation**

## Species Presence

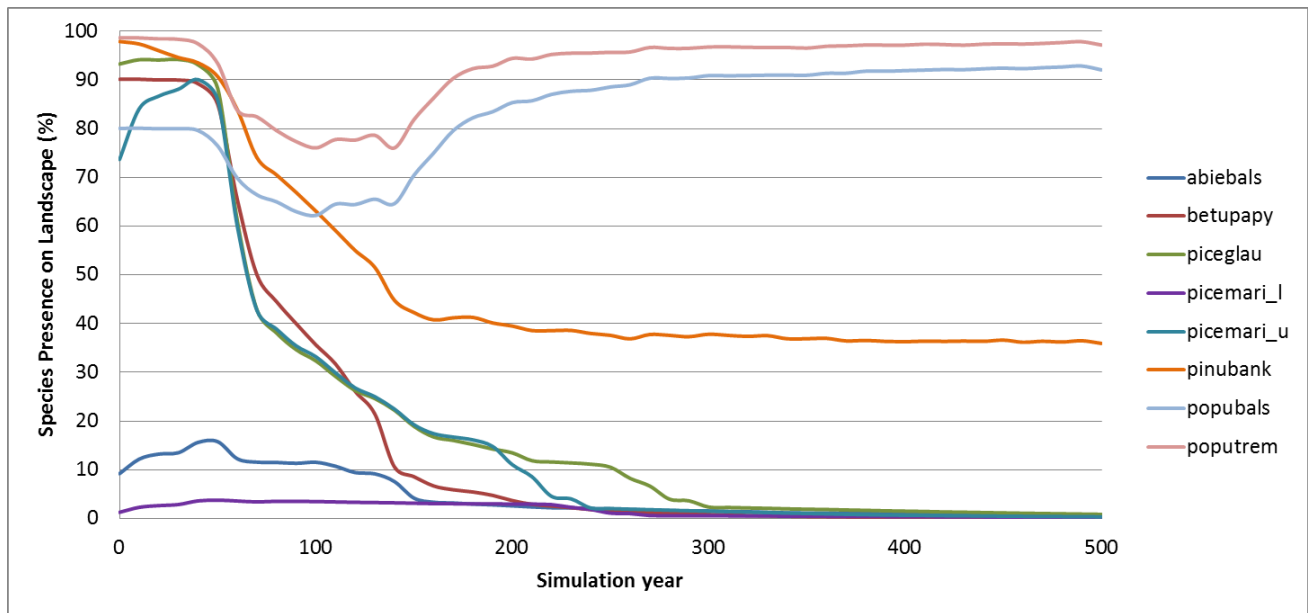
Species presence is assessed as the proportion of cells that contain the species of interest. Figure 22 and 23 show the overstory species presence in the Island Forests, for each 500 year simulation, under future climate scenarios with fire on the landscape. The determination of what trees were in the overstory was based on the ratio of the species age to the age of the oldest species found on the site. When the ratio is greater than 0.66, the species was considered to be within the overstory (ArborVitae Environmental Services and KBM Forestry Consultants Inc. 2006).

In Figure 22 and 23, there is an initial decline in abundance of all species within the first hundred years. The patterns of these declines varies from each simulation that the overall pattern is essentially the same. After the first 100 years, most species begin to stabilize on the landscape. Trembling aspen and balsam poplar become the most dominant species on the landscape during both of the 500 year climate change simulations. Trembling aspen has the highest level of presence on the landscape, hovering around 97%. Balsam poplar comes in a close second, stabilizing around 92% for both simulations. These two species seem to be the most suited for reproduction and survival when increased fire is present on the landscape. This is most likely due to their life history characteristics, aspen for example, develop shallow and extensive lateral roots that undulate and meander for great distances without tapering.

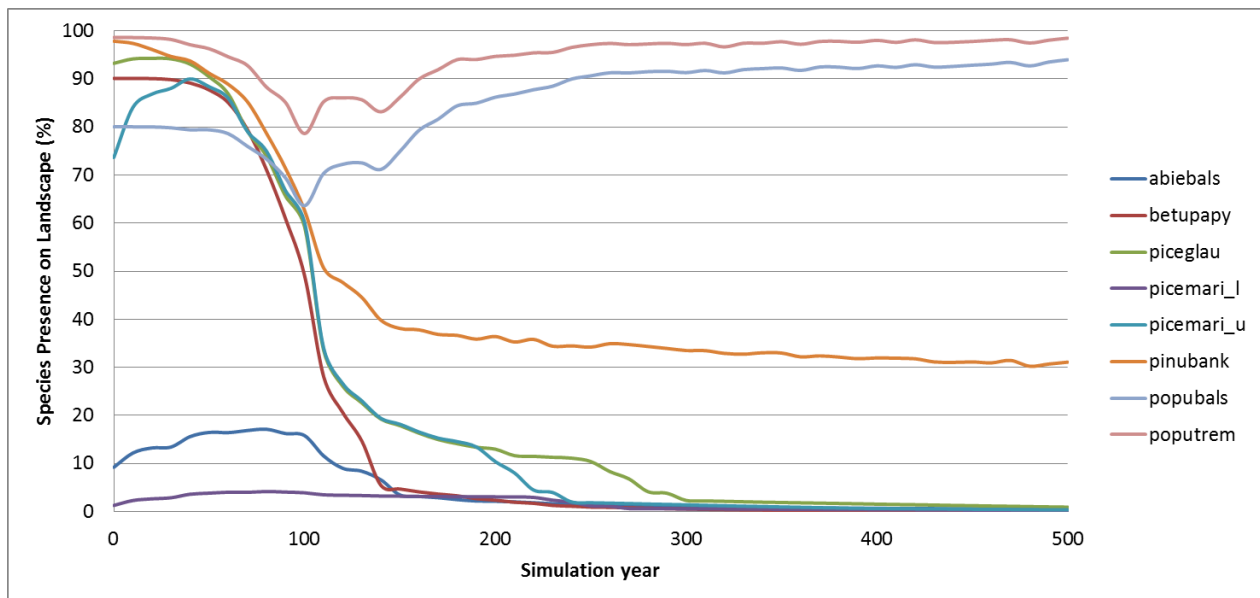
These roots have the ability to produce suckers, and allow the species to regenerate quickly following a fire (Klinka et al. 2000). Trembling aspen is classified as being at medium risk to fires, as it can regenerate at fire intervals as short as three years. Balsam poplar also has lateral root development and is classified as a low risk class to fire (Klinka et al. 2000). These attributes, most likely have these two species the ability to flourish under future conditions. The third species that is most dominant on the landscape is jack pine. Due to its serotinous cones, jack pine is highly tolerant to fire conditions. Jack pine stabilizes at about 30% under the historical simulation, at 38% under the 2050s simulation, and 30% in the 2100 simulation. This shows that under climate scenarios and increased fire, jack pine initially increases then slowly decreases back down to current levels on the landscape. Increases in fire may be initially increasing the survivability of jack pine as it is highly tolerant to fire and the increase in fire frequency in the 2050s may give it the ability to outcompete other species. However, the decrease shown in 2100s may also indicate that a threshold is reached, and fires may be now occurring too frequently for jack pine to fully mature and produce seed.

The remaining species on the landscape follow similar patterns throughout both simulation periods. Black spruce initially increases on the landscape until simulation year 100, and then slowly decreases, remaining as a very small presence on the landscape. White birch, white spruce, and balsam fir significantly decrease on the landscape over the 500 year simulation. White birch and balsam fir disappear at about year 250 for all three simulation periods. White spruce remains on the landscape a little longer; reaching year 300 before it is almost disappears. This is likely due to the fact that white spruce has a longer lifespan than white birch and balsam fir.

This model evidently has a tendency to simplify the species composition of forest stands, as evidenced by the initial declines in all species. This may suggest that some of the species reproduction parameters may not be set properly, or perhaps that this for successional forces are too complex to model with much accuracy, especially in the case of species that are already less abundant on the landscape. What can be surmised from these modeling efforts is that trembling aspen, balsam poplar, and jack pine will be the most dominant species on the landscape under climate change. Trembling aspen and balsam poplar will remain the two most dominant species within this region. Therefore, management efforts may be needed to increase the likelihood of other species remaining landscape.



**Figure 22: Overstory Species Presence under climate change for a 500 year LANDIS-II simulation under “2050s fire” (2x historical) conditions**

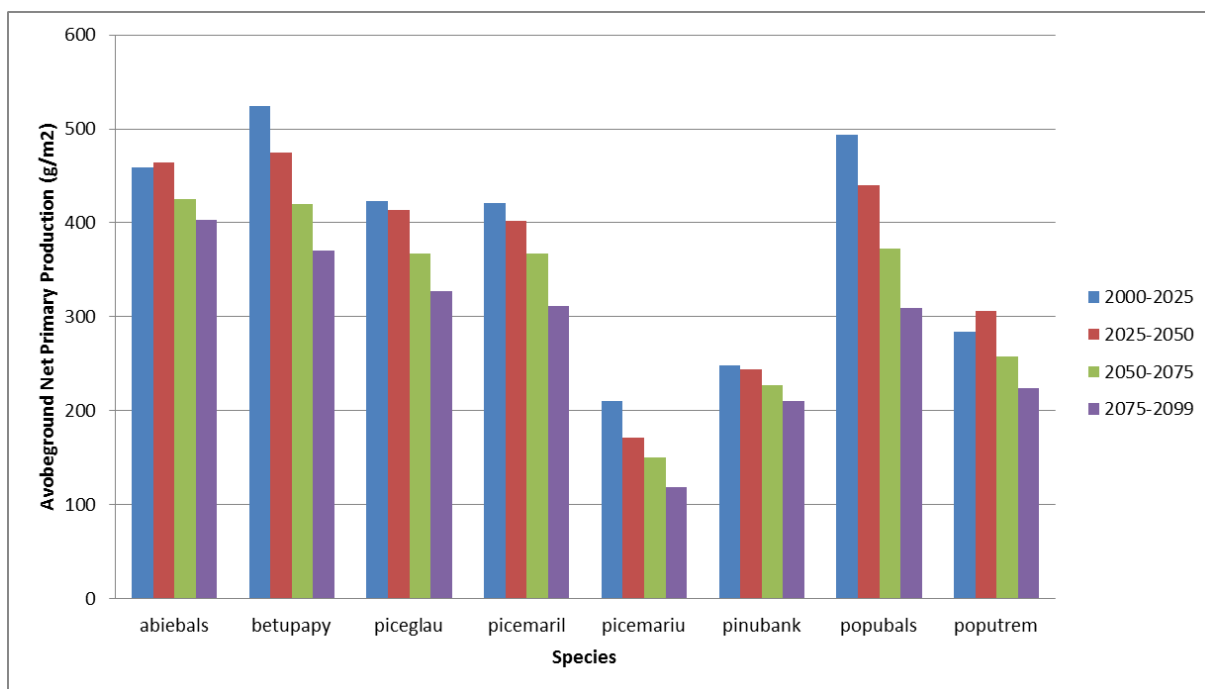


**Figure 23: Overstory Species Presence under climate change for a 500 year LANDIS-II simulation under “2100s fire” (3x historical) conditions**

### Above-Ground Net Primary Production

Above-ground net primary production (ANPP) for each species in the Island Forest region was calculated using the PnET-II model (Figure 24). For all of the species, ANPP trends downward in the future with the lowest values occurring at the end of the century. Balsam fir and trembling aspen show an initial increase in ANPP from 2025-2050, but this is short lived and ANPP declines in the following years. These results show that under the CRCM4.2.3-A2, the Island Forests will likely become less productive over

time. The decrease in ANPP varies by species, with the largest decrease in ANPP occurring in balsam poplar with a fall in ANPP by  $200 \text{ gC m}^{-2}$  at the end of the century. Jack pine seems to be the best adapted species under this scenario, with only a small decrease in productivity by 2100. Other studies examining the effects of climate change in forest regions have shown quite contradictory results with regards to NPP in forest regions, including an increase in NPP (Peng and Apps 1999, White et al. 1999) or a decrease in productivity (Hogg and Hurdle 1995, Hogg and Bernier 2005). Decreases in boreal forest productivity are usually associated with areas of high disturbances and low soil moisture. In the Island Forests, this would account for the downward trend in NPP for all species, as this region is associated with low soil moisture due to sandy soils and its far southern location at the edge of the boreal forest. Therefore, it is not surprising to see that this model predicts ANPP decreases in all species across this region.



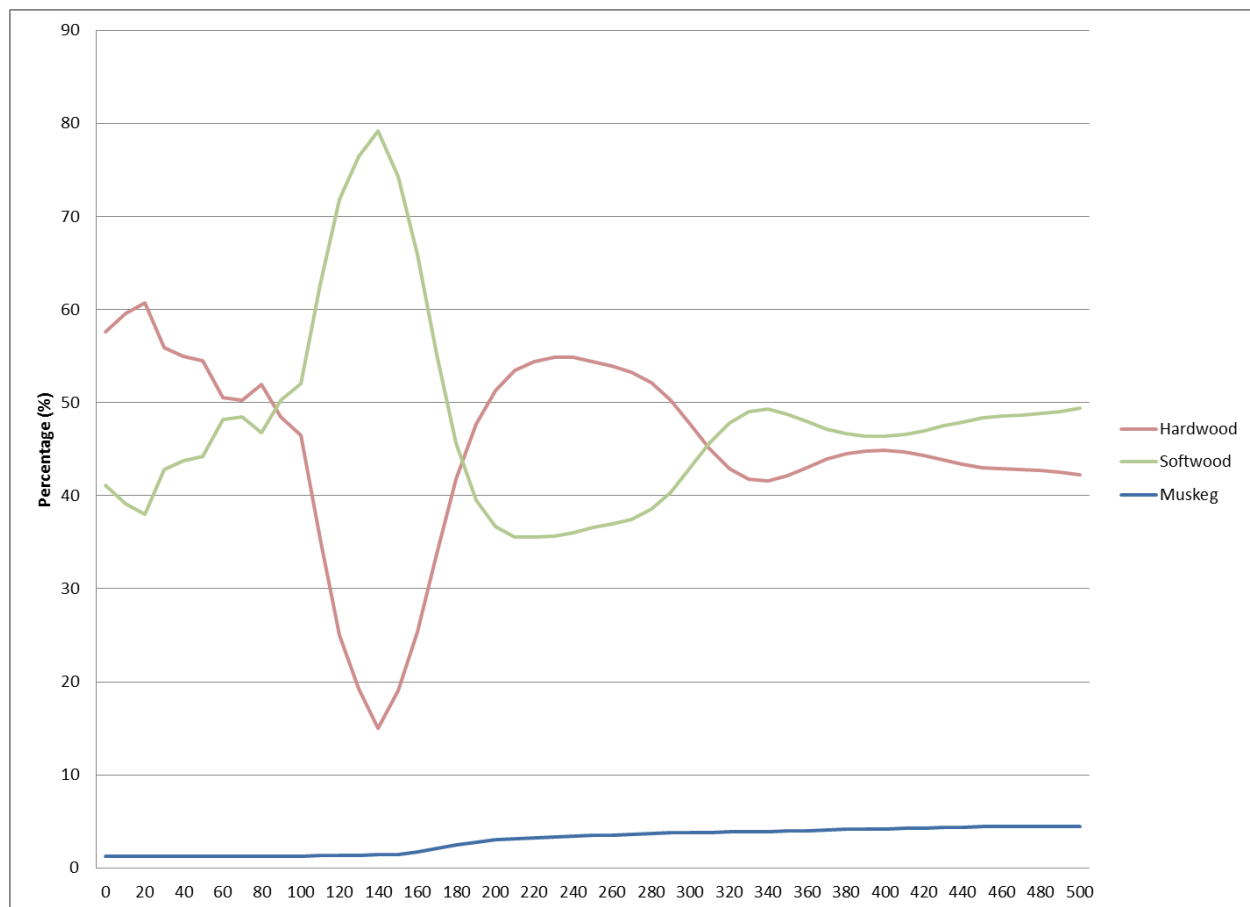
**Figure 24: Aboveground net primary production ( $\text{g/m}^2$ ) for 4 time slices (2000-2025, 2025-2050, 2050-2075, and 2075-2099) for each species in the Island Forest using climate data from the CRCM4.2 model.**

## Forest Landscape Composition

A Reclass extension was run in LANDIS-II which combined all the muskeg regions, hardwood species (trembling aspen, balsam poplar, white birch) and softwood species (jack pine, white spruce, black spruce, and balsam fir) on the landscape into these basic categories for every year of the simulation run. The initial Island Forest landscape, shows about a 58% coverage of hardwood, and a 41% of softwood. Muskeg regions initially take up a very small percentage of the landscape, about 1%. Figure 23 and 24 show the current landscape composition of hardwood, softwood, and muskeg forest regions, and how this landscape changes through simulation time under successional dynamics but with no fire on the landscape. All simulations were done over a 500 year period, after 300 years all the simulations reach



equilibrium. With no fire present, we can see that over time muskeg areas grow on the landscape, while hardwood and softwood stands fluctuate through time, reaching steady-state at around 300 years with softwood slightly more dominant on the landscape. These initial simulation runs, had no fire disturbances, and therefore, results were based purely upon successional dynamics of the species in the model. Muskeg regions are also responding to changes in hydrology and moisture availability. This shows that on this landscape, *ceteris paribus*, hardwood and softwood species will likely remain around similar levels on the landscape but will change in distribution over time.



**Figure 25: Landscape dynamics between hardwood, softwood, and muskeg species in the Island Forests under model simulation for 500 years with no disturbances**

Successional dynamics and species dominance changes greatly when disturbances, such as fire, are added on the landscape. Figure 26 and 27, show 300-500 year simulations under historical conditions and future conditions with fire. Climate change seems to have little effect on the distribution of hardwood and softwood species in the future. Fire seems to be the dominant force on this landscape, as shown under the historical simulation where hardwood becomes the dominant species and quickly rises to take over about 90% of the landscape by year 300. The same pattern is seen under both climate change scenarios, year 2050 climate and 2100 climate, with hardwoods becoming the dominant species on the landscape. Even though fire increases on the landscape under future conditions there seems to be little change in the outcome of hardwood versus softwood species on the landscape. There may be a

slight increase in hardwoods species from historical to 2100s, but the increase is only by a small percentage.

It seems as though LANDIS-II favors hardwood species, when fire is present on the landscape. From Figure 12, we can see that the successional dynamics linked in the model are functioning properly. It seems that when fires appear on the landscape, that hardwood species, namely aspen and balsam poplar, become highly competitive and dominate the landscape. We could see this pattern earlier with species presence on the landscape, where balsam poplar and trembling aspen become the most prominent species on the landscape, while jack pine decreases but remains the third dominant species on the landscape. So although jack pine is present, pure softwood stands become mostly absent from the landscape when fire is present. Whether or not these simulations will prove to be accurate, LANDIS shows that aspen and balsam poplar will likely be the best species for survival under climate change and increased fire.

It is surprising that increase fire on the landscape showed such little change on forest composition between hardwood and softwood species. It could be that some parameters need to be improved within the life history attributes of each species. The base fire model is also a very simplistic fire model; therefore, it may not be capturing the true effects of fire on this landscape. In future work we will compare the dynamic fire model with the base fire model, to see when the results of landscape composition would change by using a more sophisticated approach to fire disturbance.

## Present Landscape Composition

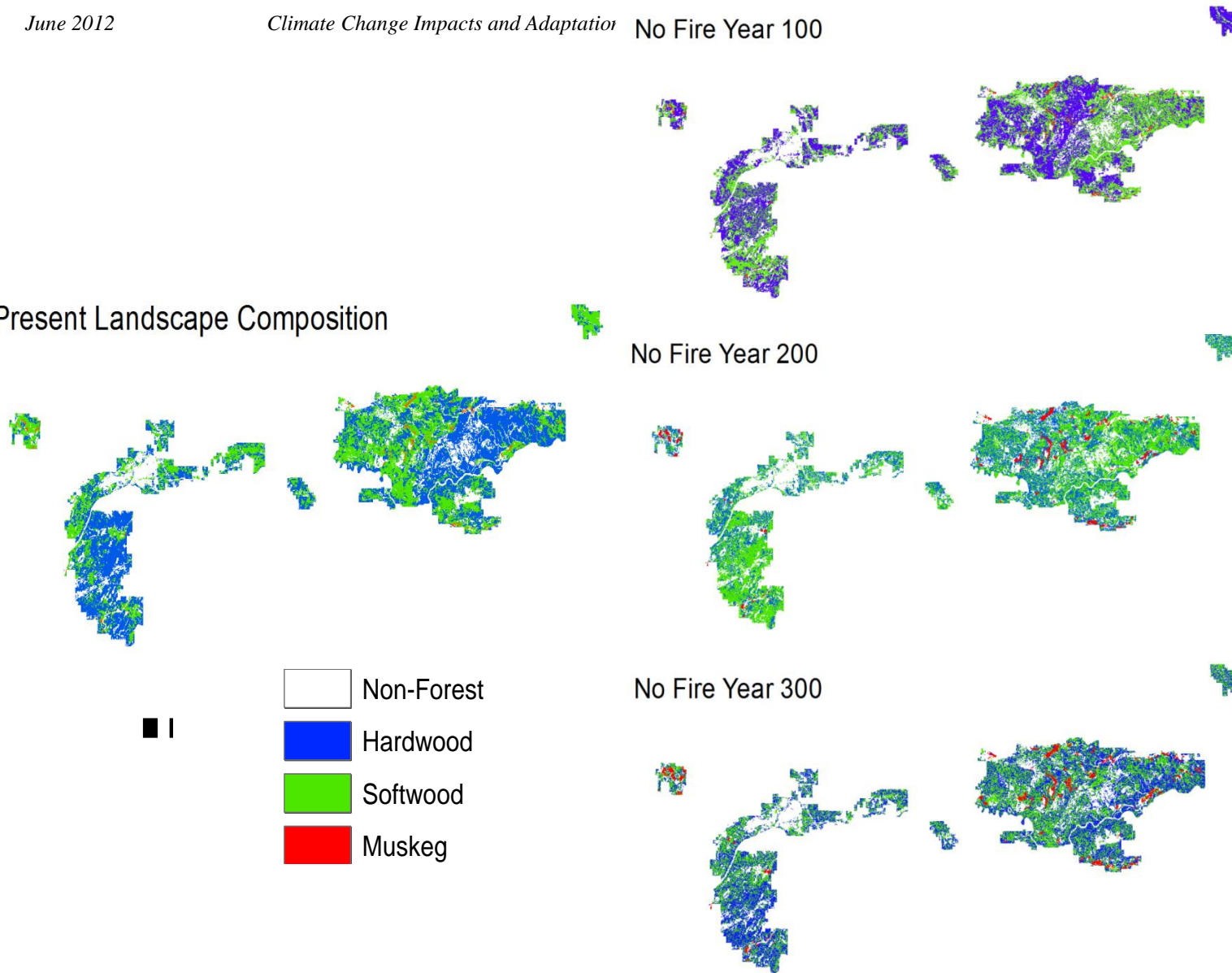


Figure 26: Landscape composition showing hardwood, softwood, and muskeg regions in the Island Forests under successional dynamics with no fire present on landscape

## Present Landscape Composition

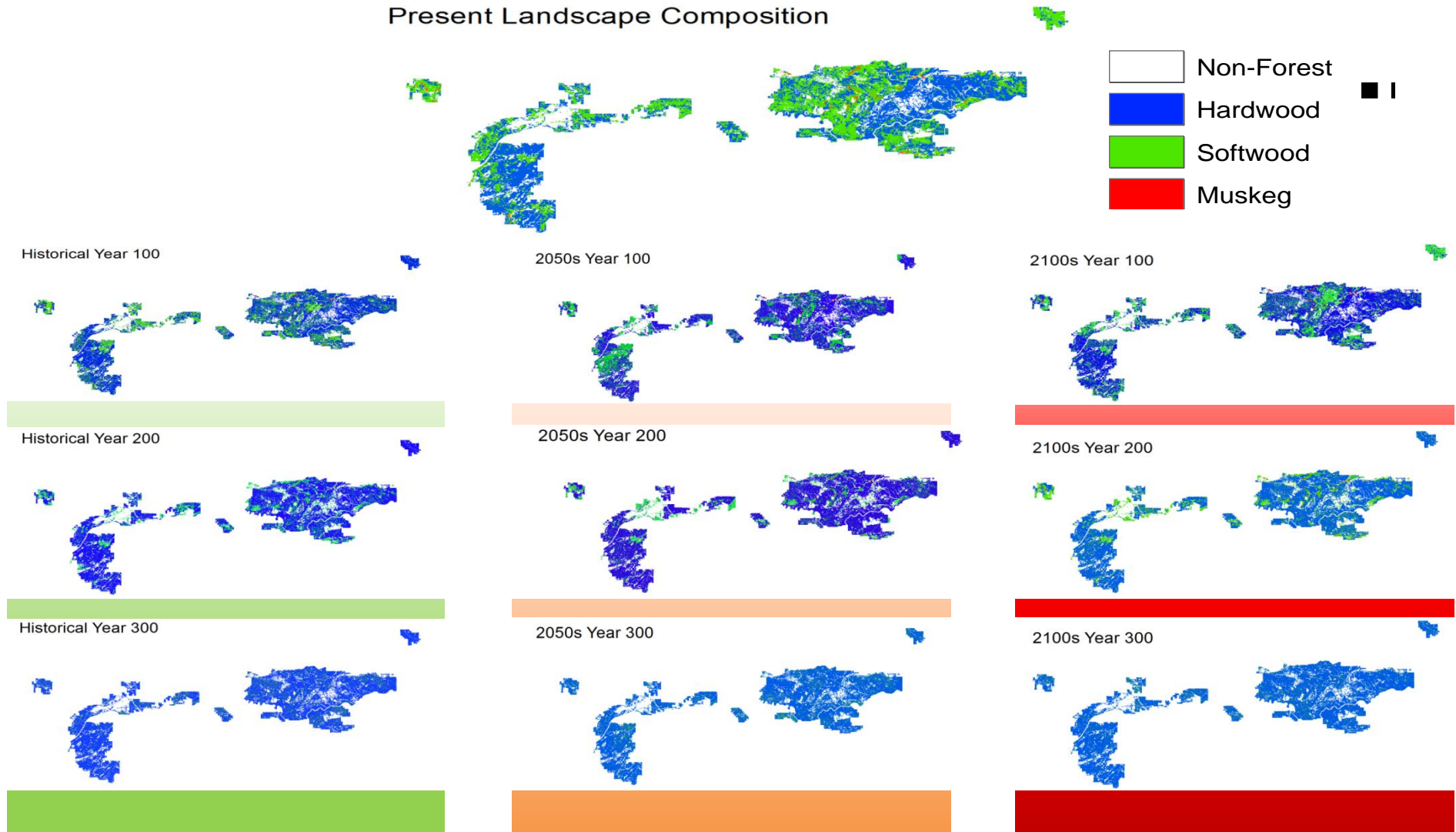
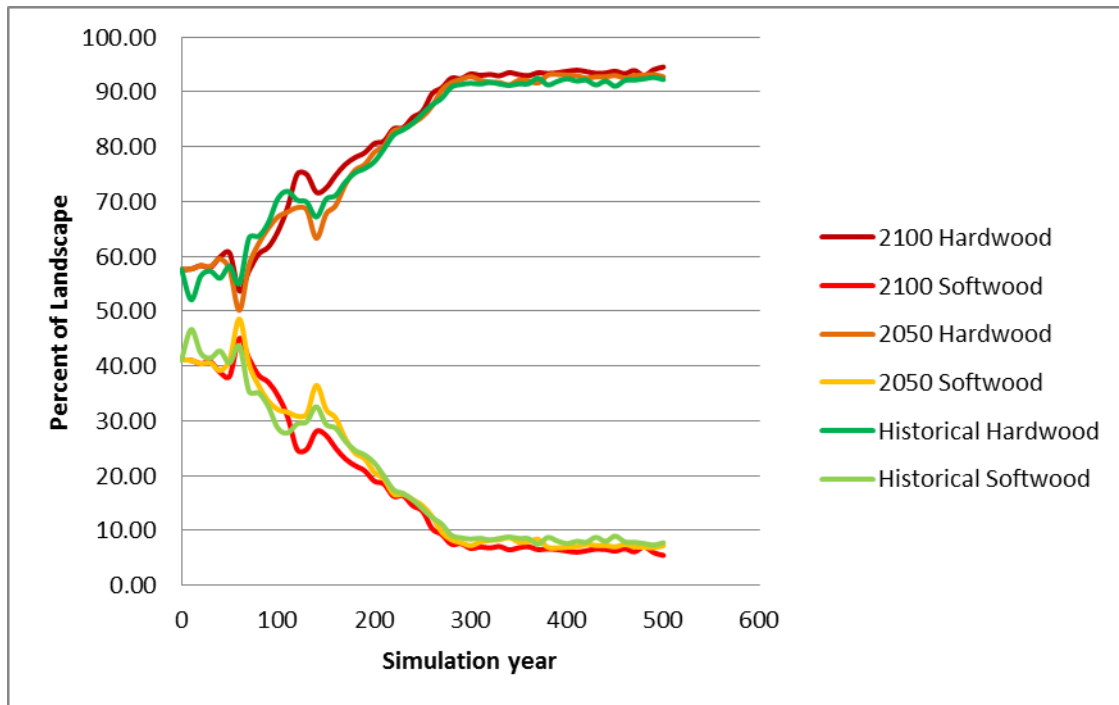


Figure 27: Landscape composition showing hardwood, softwood, and muskeg regions in the Island Forests under successional dynamics, fire, and climate change.

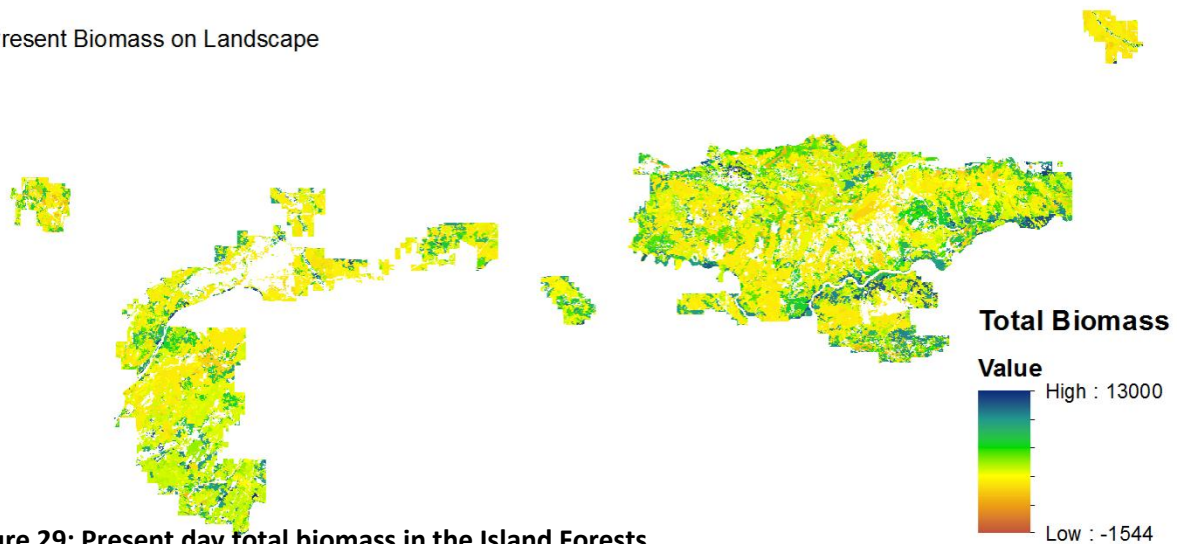


**Figure 28: Percent of landscape composed of hardwood species and softwood species over 500 year simulation under Historical conditions and climate change**

## Biomass

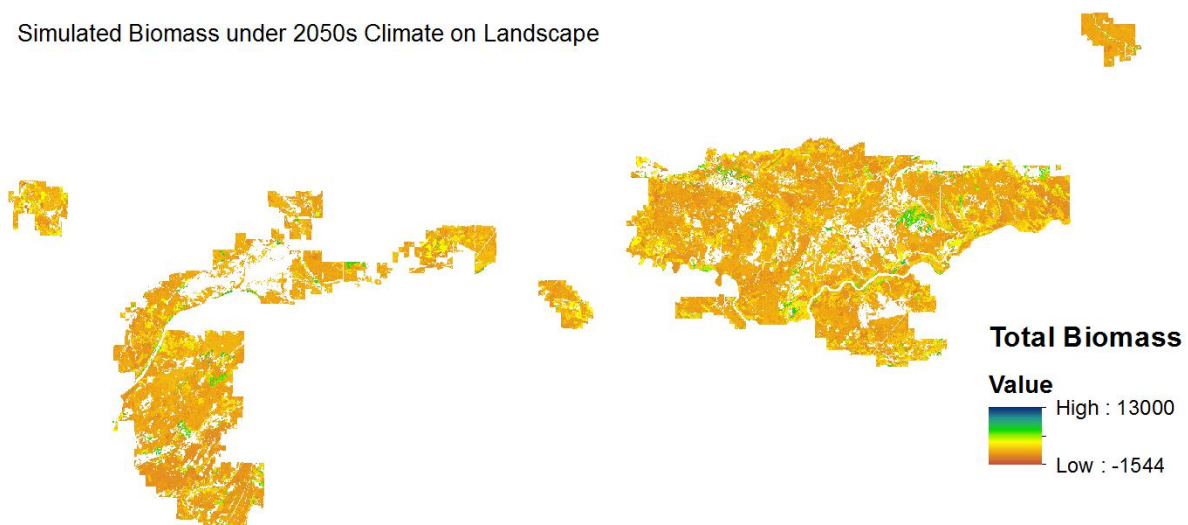
Total biomass for the present day landscape is shown in figure 29. Regions with high amounts of biomass are shown in dark blue and green and represent ecoregions such as balsam poplar and trembling aspen, trembling aspen and white birch, balsam poplar and white spruce. Areas with lower biomass are shown by yellow to light orange colors in these represent areas composed of jack pine and some white spruce. The following two figures (Figure 31 and 32) show simulated biomass on the landscape under 2050s and 2100s climate. From these two diagrams we can see that overall biomass on the landscape decreases across all ecosystems.

Present Biomass on Landscape



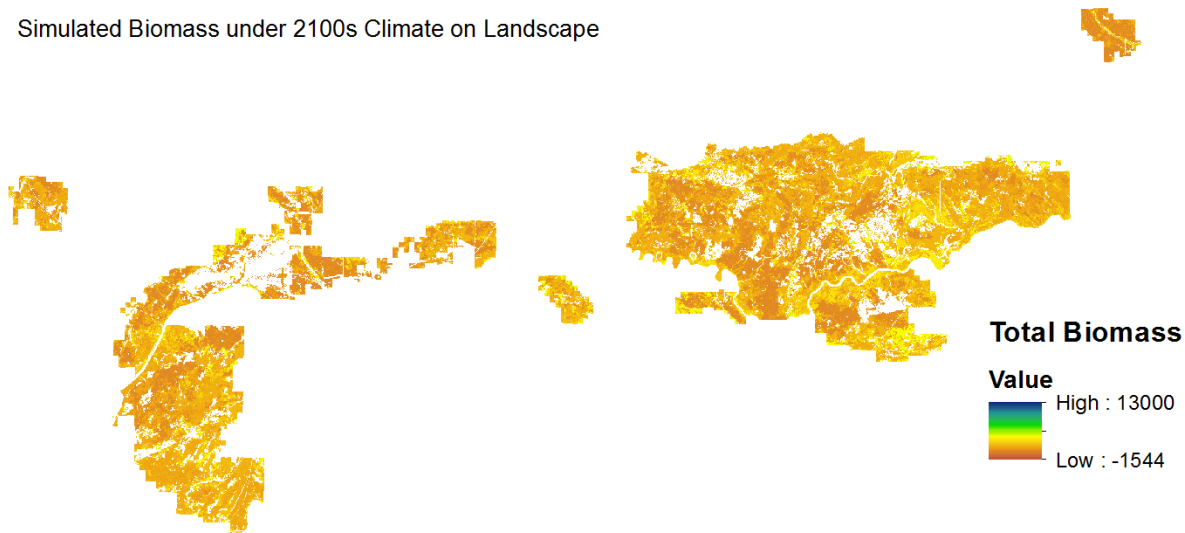
**Figure 29: Present day total biomass in the Island Forests**

Simulated Biomass under 2050s Climate on Landscape

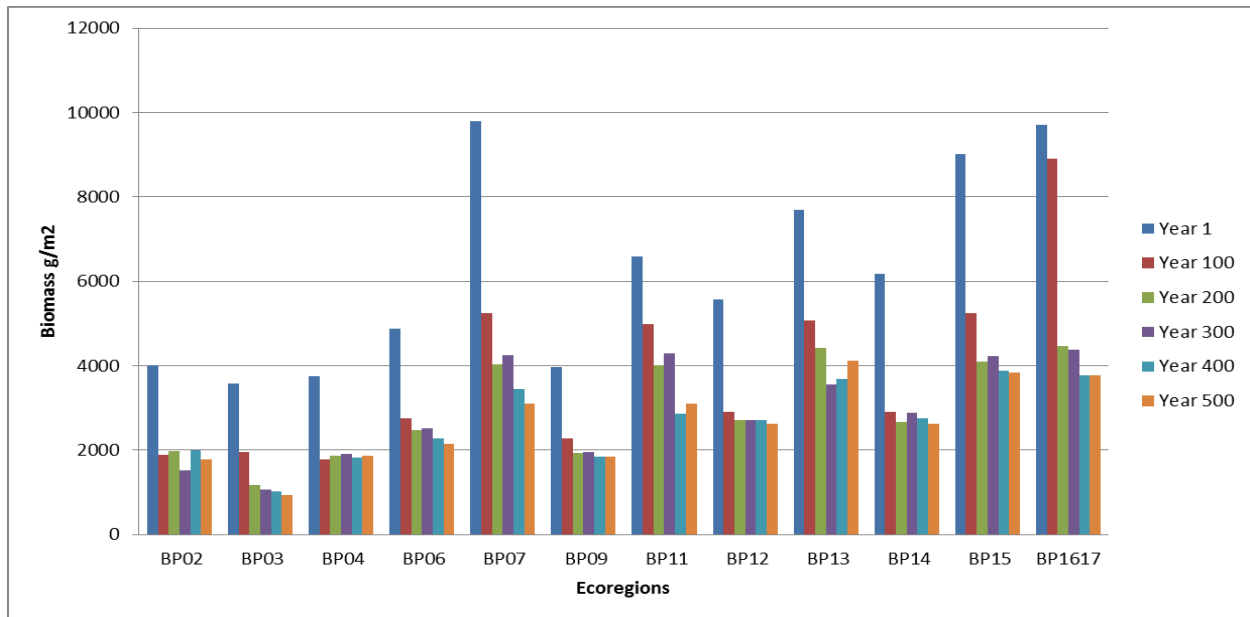


**Figure 30: Simulated biomass under 2050s climate in the Island Forests**

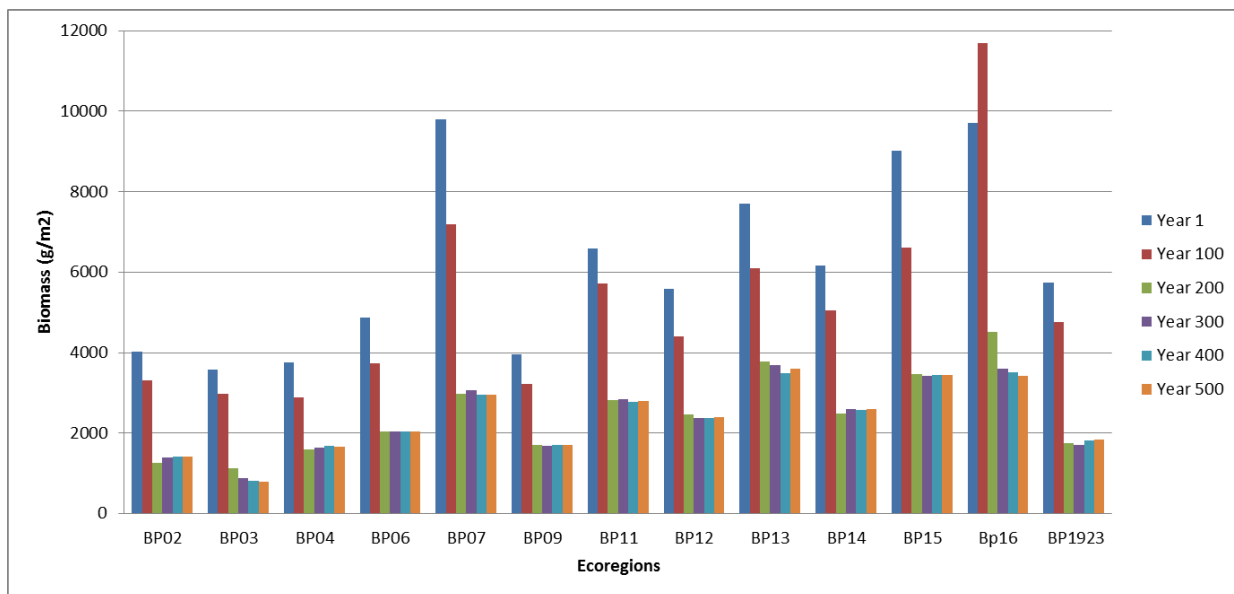
Simulated Biomass under 2100s Climate on Landscape

**Figure 31: simulated biomass across the Island Forests for the 2100s climate change scenario**

This corresponds with what we know about non-productive regions in this area and earlier results of ANPP discussed in this paper. ANPP is linked to biomass; areas with higher ANPP will also have greater biomass because ANPP is a measure of productivity. The more productive a site, the more biomass it will produce. The maps of biomass show the relative configuration of modeled biomass across the Island Forests, however if we want to delve deeper we can examine figures 30, and 31 which show biomass for each Ecosite across the entire simulation time under both future climates. These graphs show that initial biomass varies across each ecoregion. Under both simulation time periods, we can see that initial biomass at drops in all of the ecosites. For many of the ecosites, there was lower biomass in the 2100s simulation relative to the 2050s. Therefore, these modeling results show that total biomass within the Island Forests will decrease for all ecoregions over the next century. Decreases in biomass can be over 4000 g/m<sup>2</sup> in some ecoregions, with the highest drops occurring in hardwood stands. Forestry managers should take note that under future climate conditions this region is likely to have lower productivity relative to current stands. Whether these stands will still be appropriate for harvest will need to be considered by forestry managers in the region.



**Figure 32: Biomass for each ecosite over the 500 years under the 2050s simulation.** Year 1 is the baseline, while the remaining years are actually averages for each 100 year period (ex: Year 100 is an average of biomass from 1 to 100).



**Figure 33: Biomass for each ecosite over the 500 years under the 2100s simulation.** Year 1 is the baseline, while the remaining years are actually averages for each 100 year period (ex: Year 100 is an average of biomass from 1 to 100).



## 7. Adaptation options for the Island Forests

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). The IPCC defines adaptation 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). Although forest ecosystems will adapt autonomously to climate change, their importance to society means that managers 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 required 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. Adaptation to climate change involves monitoring and anticipating change and undertaking actions to avoid the negative consequences and take advantage of potential benefits of those changes (Levina and Tirpak 2006).

The largest obstacle 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 considers the impacts of climate change on the forest and the forest's 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 promise 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 (Spittlehouse and Stewart 2003, Millar et al. 2007). It is also important to realize that under uncertain futures, there is no single approach that will fit all situations.

The final step in this report is to consider a wide range of potential adaptation options that are appropriate under current and future climate conditions (Sustainable Resource Development, 2010). The results from this section will provide a toolkit of ways to achieve objectives by enabling the identification of a wide variety of possible adaptation options that can be used to increase adaptive capacity within the Island Forests. Early adaptation is important because it increases adaptive capacity while reducing vulnerabilities and demonstrates effective risk management (Sustainable Resource

Development, 2010). The list of adaptation options is found in Table 18. Forestry managers interested implementing these initiatives on the landscape should first consider hosting a focus group, workshop or brainstorming session with a group of stakeholders to consider whether these options are viable or even economical. To aid with decision making, Table 18 lists adaption options according to an organization's capabilities in four critical areas: Governance, People, Technology, and Process. It is also important to note that this list is not exhaustive but meant to help guide forest practitioners along the path to adaptation within forest management. The best adaptation options will probably come from practitioners themselves, who are familiar with the area and management needs of the Island Forests.

In order to increase robustness and help deal with uncertainty, a no-regrets strategy and a reversible strategy category are included in Table X. Adaptation options which are considered no-regrets and reversible are the most capable of coping with the high level of uncertainty associated with climate change (Hallegatte, 2009) and may help decision makers choose the best adaptation strategy under climate change.

### ***"No-Regrets" Strategies***

A "no-regret" strategy indicates that an adaptation option provides benefit to society regardless of whether climate change occurs or not. In Table 18, an adaptation option which is a "no-regret" strategy in every situation it gets marked with double plus signs ("++"), if it is only a "no-regret" strategy in some situations it will be marked with a single plus sign ("+"). See (Hallegatte 2009) for more details.

### ***Reversible strategies***

It is also sensible to favor strategies that are reversible and flexible over irreversible choices (Hallegatte 2009). This is especially important when it comes to making decisions with regard to climate change because flexible options can be changed with a changing climate. Often something that is appropriate for adaptation to climate change right now, maybe not be so in the future. Therefore, strategies that change be easily changed when new information becomes available should be favored over other options that are rigid. Any adaptation option that is identified as a reversible strategy will be marked with a plus sign ("+").

**Table 18: List of adaptation options for the Island Forests that could be used to reduce this region's vulnerability. Listed according to organization capabilities with notification whether an option is a "no-regret strategy" or reversible**

High Risk Impacts	Organizational capabilities	Adaptation options	No-regrets strategy	Reversible
Water Regulation  Drought and excessive moisture	Governance	Address any policies that may not allow the plantation of exotic species	++	+
	People	Increase communication of knowledge across disciplines and between forestry managers	++	+
	Technology	Develop integrated monitoring system that can detect large-scale changes in the island forests, especially in areas prone to drought	+	+

High Risk Impacts	Organizational capabilities	Adaptation options	No-regrets strategy	Reversible
		or excess moisture		
		Improve drought hardiness through genetic manipulation	+	
	Process	Reforestation with drought sensitive species or provenances (even exotic species)	+	
		Replace current drought sensitive species in areas prone to drought stress	++	
		Pre-commercial thinning of stands to conserve soil moisture	+	
		Schedule reforestation activities during the optimal periods	+	+
<b>Habitat and Landscapes</b>  Species shift and fragmentation		Replace tree species with alternatives that are more tolerant of forecasted climate conditions	+	
	Governance	Work with others to ensure that stressors outside the control of forest managers are minimized (e.g.; pollution)	++	+
		Address any institutional and policy barriers that limit the ability to adapt to climate change (e.g.; planting exotics, intensive forest management, seed transfer zones)	++	+
	People	Staff training and awareness activities	++	+
	Technology	On the ground monitoring of native species can indicate the directions of change and appropriate response at local scales	++	+
		Surplus seed banking	+	+
	Process	Explore opportunities for assisted migration of populations and species	+	
		Improve disturbance management to help maintain existing forests	+	
		Mitigate habitat loss by habitat enhancement strategies	++	+
		Reduce human-caused stressors that may cause habitat loss or	++	+

High Risk Impacts	Organizational capabilities	Adaptation options	No-regrets strategy	Reversible
		fragmentation; such as managing tourism, recreation and grazing impacts  Maintain forest edges  Enhance and promote ecosystem function by restoring degraded areas and maintaining genetic diversity and continuing ecosystem health	  ++  ++	
<b>Pest regulation</b> Insects and disease	Governance	Climate change policy for pest regulation	+	+
	People	Increase public education and awareness about invasive species  Implement public programs on invasive species and a number to call if the species is spotted	 ++  +	
	Technology	Create novel pheromone applications to attract insects  Increase investment in monitoring equipment for invasive species and pests to allow implementation of early detection and rapid response	 +  ++	
	Process	Prevent invading pests from becoming permanently established by controlling when populations are small  Adjust harvest schedules to harvest stands most vulnerable to insect outbreaks  Plant genotypes that are tolerant of drought, insects and disease  Reduce disease losses through sanitation cuts that remove infected trees  Use prescribed burning to reduce fire risk and reduce forest vulnerability to insect outbreaks  Controlling catastrophic insect or vegetation disturbances by biological, chemical or physical controls	 ++  +  ++  ++  +  +	        +

High Risk Impacts	Organizational capabilities	Adaptation options	No-regrets strategy	Reversible
		Take early defensive actions at key migration points to remove or block invasions	++	
<b>Timber</b>  - Fire -Reduced regeneration -Supply and revenue	Governance	Policy for fire management under climate change	++	+
		Establish reforestation standards that incorporate Sustainable Forest Management under climate change	++	+
		Increase investment in forest health monitoring and control	+	
		Remove barriers and develop incentives to adapt to climate change in forest management policies	+	+
		Ban on debris burning practices	+	
	People	Educate people on fire smart 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	+	+
	Technology	Include climate variables in growth and yield models to improve prediction on the future development of forests	++	
	Process	Decrease rotation length to reduce risk of exposure to hazards such as storms or fires	++	
		Acceleration of FireSmart Strategies to protect forest communities	++	
		Implement forest landscape planning to create future forests with reduced fire risk, insect and disease susceptibility	+	
		Explore opportunities for assisted migration of highly productive populations and species to new favorable areas create by climate change	+	

High Risk Impacts	Organizational capabilities	Adaptation options	No-regrets strategy	Reversible
		Enhance forest growth through forest fertilization or irrigation	+	
		Retain forest cover on the landscape by maintaining a diversity of age stands and use forest harvest activities to help create more age-stand diversity	+	
		Manage for fire creating and maintain fire breaks where necessary	++	
		Redistribution of fire-dependent forest types away from human ignition sources	+	
		Modify forest structure to reduce the potential for fire spread	++	+
		Increased fuel management through: <ul style="list-style-type: none"> <li>- prescribed burning</li> <li>- Understorey biomass removals/ grazing</li> <li>- Species that regenerate after fire</li> <li>- Landscape mosaics that include species with reduced flammability</li> </ul>	+	
		Maintaining or expanding infrastructure for direct attack on fire	+	+
<b>Carbon storage</b>  Declining bio-productivity and forest health	Governance	Provide incentives and remove barriers to enhance carbon sinks and reduce greenhouse gas emissions	+	+
		Provide opportunities for forest management activities to be included in carbon trading systems	+	+
	Technology	Use low impact harvesting activities to reduce the impact on soil disturbance	+	
	Process	Enhance forest growth and carbon sequestration through forest fertilization	+	
		Modify thinning practices and rotation length to increase growth and turnover of carbon	++	

High Risk Impacts	Organizational capabilities	Adaptation options	No-regrets strategy	Reversible
		Reduce spacing and thinning to increase recovery after dry periods	+	
		Minimize density of permanent road network to maximize forest sinks	++	
		Decommission and rehabilitate roads to maximize forest sinks	++	
		Identify forested areas that can be managed to enhance carbon uptake	+	
		Restore the productive forest cover on stands that did not regenerate properly after harvest	++	
		Establish new plantations which replace low productivity forest vegetation on fertile soils	+	
		Identify areas that are degraded and can be rehabilitated	+	
		Decrease the impact of natural disturbances on carbon stocks by managing fire and forest pests and by enhancing forest recovery after a disturbance	+	
		Used containerized stock to reduce drought risk	+	
		Increase genetic or species diversity in seeded and planted stands	+	
		Consider the right suite of attributes of forest tree populations for future climates such as higher temperature and drought tolerance and capacity to take advantage of increased levels of CO <sub>2</sub>	+	

Implementing many adaptation options will likely be costly and research is needed to provide sound frameworks for cost-benefit analysis (Keenan 2012). Successful risk management will include:

- maintaining and managing infrastructure

- dissemination of knowledge of potential climate impacts and suitable adaptation measures to decision makers at both practice and policy levels
- robust monitoring system to provide early warning on climate change impacts

Adaptation is inherently a social process and forests are social-ecological systems that involve both nature and society (Innes et al. 2009). Determining tradeoffs between management objectives is important in sustainable forest management as many proposed adaptation measures may change the balance between current objectives and stakeholder interests (Keenan 2012). Therefore, adaptation decisions will require difficult social choices about what society values most about forests and what society might be prepared to lose, while the diverse values and interests of different stakeholders can impede efforts to reach a consensus on longer-term forest management goals under a changing climate (Seppala et al. 2009). Adaptation options could be further examined in LANDIS by implementing different harvesting practices or other management interventions and determining how these options changed the vulnerability of the Island Forests.

## 8. Conclusions

This study addressed many of the initial questions posed by forestry managers at project initiation. End users of this product will need to change the way they make decisions, to include climate change and uncertainty in their everyday operations. It is important to incorporate future climate predictions and adaptation options into management plans, also called “mainstreaming” (Smit and Wandel 2006). The consequences of climate change and its direct effects on the Island Forests have been analyzed in this report. The next step is determining how to apply this knowledge to on the ground applications; this will have to be at the discretion of the forestry managers.

### ***Future fire scenarios and their impact on future wood production***

Predictions from Bashi et al., (2008) forecast that under the CGCM2 A2 scenario, fires could increase on the boreal forest landscape by 5.5x historical values by the year 2100. If true, the Island Forests could be eliminated, resulting in widespread tree mortality as shown by attempting to model this effect in LANDIS-II. Ecological processes that are important to tree mortality, may lead to forest ecosystem retreat, resulting in ecological regime shifts. Such ecological regime shifts can be considered to be a direct consequence of regional scale forest dieback; tree species are expected to shift their geographical range pole wards or to higher elevations as global warming occurs (Loarie et al. 2009, Doak and Morris 2010, Wang et al. 2012). Future environmental conditions may not be suitable for the current ecosystems that reside in the Island Forests, and therefore, may be succeeded by novel ecosystems comprised of pre-existing species, invading species, or their combination (Littell et al. 2010), consecutively changing ecosystem composition, structure and diversity (Wang et al. 2012). Grasslands are likely to replace trees in the Island Forests under increased fire frequency because they are better suited to deal with frequent fire events. But what types of plant communities will form is unknown. Currently these suppositions are based on general ecosystem principles, as LANDIS is unable to model shifts in ecoregions or invading species such as grasses. The main point to take from this is that under extremely high increases in fire intensity and frequency, the Island Forests are at great risk to becoming



succeeded by grasslands or other novel community types. As severe tree mortality will likely occur under these new conditions, trees may be unable to regenerate and produce seeds quickly enough survive under such harsh fire conditions. Adaptation management will likely be unsuccessful at this point to aid in the continuation of the Island Forests, at least in any condition in which it now exists.

If fires were to only increase by 1.2 and 3x historical values, forest communities would likely be able to remain on the landscape according to modelling analyses. However, species presence and dominance would likely change overtime. Under this potential fire future, forestry managers would have the ability to introduce adaptation measures to help the forest species to adjust to increased fire by implementing options such as:

- prescribed burning
- Understory biomass removals/ grazing
- Planting species that regenerate easily after fire
- Constructing landscape mosaics that include species with reduced flammability

According to LANDIS, species such as trembling aspen and balsam poplar will become the most prominent species under future climate warming and increased fire (1.2x and 3x historical fire). As discussed earlier, these two species are likely the most successful due to their life history attributes (Table 10), which are similar for both species. The ability to re-sprout post-fire at any age, and reach sexual maturity after 10 years, gives these species the key to outcompeting other species under a highly fire dominated landscape. For example, trembling aspen is able to regenerate at fire intervals as short as 3 years. Some of these life history attributes may be a bit simplified and it should be noted that as with any modeling exercise, these outputs are very general. Therefore, although LANDIS shows that these two species dominate the landscape at the end of each 500 year simulation under climate change, it will likely not be to the same extent noted here, as there are many other interacting factors that cannot be accounted for in this modeling exercise, such as drought and pests. Forest managers can conclude from these results that trembling aspen and balsam poplar will likely be good candidates for successful reestablishment under future climate change and fire. Management should then take into account whether they wish to promote these two species on the landscape, or focus on helping other species survive in the Island Forests.

From a management perspective, trembling aspen can be considered a highly productive tree species, producing high yield of wood in a relatively short time (about 50 years) (Klinka et al. 2000). This species also display wide genetic diversity, including polyploidy, which may be used in future breeding programs to produce individuals with superior form, wood properties, and growth rate, perhaps even under climate change. This tree produces wood that is light and soft and can be used for lumber, oriented strand-board, and pulp (Klinka et al. 2000). Balsam poplar produces in a short time high yields of wood suitable for mechanical pulping and is another productive species (Klinka et al. 2000). Given these characteristics, forest management could consider the benefits of these two hardwood species and how management and forestry products may change under climate change.

Increases in fire also cause increased fire probability on the landscape, with certain areas burning more frequently than others. According to the landscape fire analysis, trembling aspen and jack pine areas

seem to have increased fire probabilities, while white spruce, balsam fir, and balsam poplar show lower chance of fire on the landscape. Fires are chosen to randomly occur on the landscape and multiple fire events may happen at one time. Each fire event begins with an ignition and in the model and will spread from point of ignition. Whether a fire continues to burn an area depends on the time since last fire and how fast fuel accumulation occurs on the landscape. Areas containing trembling aspen and jack pine exhibit high fire frequency likely because they are the most frequent ecosystems on the landscape and are more likely to be burned.

*How does climate change affect wood supply in the future?*

LANDIS-II modeling shows that much of the Island Forest landscape will be greatly affected by climate change and fire. The percentage of hardwood species and softwood species will drastically change. Hardwood species such as aspen and poplar dominate the landscape under climate change simulations. Regions composed solely of softwood will exist on less than 10% of the landscape area, while hardwood species will increase to cover over 90% of the area. This corresponds with species presence calculations, which showed that aspen, poplar, and jack pine will be the three dominant species on the landscape. Therefore, wood supply in the Island Forests will likely be mainly from hardwood species, and forestry products will likely have to be focused on products from trembling aspen and balsam poplar.

Aboveground Net Primary Production and total biomass (Figure 24, 30, 31, 32 and 33) show that the productivity of the landscape declines for all species and ecoregions across the landscape by the end of the century. The species least effected by decreases in productivity is jack pine, which due to its preference for poor soils and ability to tolerate harsher conditions was least affected by increases in temperatures. The most significant drop in primary production can be seen in balsam poplar, which is interesting because it becomes one of the most dominant species on the landscape according to species presence and landscape composition. It is important to note here that the ANPP results do not account for increased fire on the landscape, but the effects of fire are included in the results for biomass. Therefore, since balsam poplar is predicted to be one of the most viable and dominant trees under future climate, as well as the species likely to drop the most in productivity. It is probably a safe assumption that overall productivity on the landscape is likely to decrease.

Results for total biomass show that this conclusion is true, as total biomass declines across all ecosites over time. Large decreases are seen in 2100's, especially after the first 100 years. Once the simulations have reached steady state equilibrium in years 200-500, biomass has dropped from current levels by more than 50% in some cases. This picture is not a positive one for the Island Forests, which are not very productive even under current conditions. Since all Ecoregions and species decline in productivity over each climate change scenario, it is unlikely that there will be areas on the landscape which will benefit from climate change.

It is also important to note that this modeling analysis has not included the effects of pests or drought, which are both predicted to be at powerful factors under climate change. For example, we have already seen the effects of extended drought on aspen in 2001 to 2003 which caused massive dieback of aspen stands along the boreal forest fringe. Along with potential and current pests, such as dwarf mistletoe

and mountain pine beetle, we can predict that these additional pressures will be highly influential on the forest. The Island Forests will be further stressed and likely exhibit further decreases in productivity and biomass.

This report has provided some insights that may be used in future management plans for the Island Forests:

- increases in area burned, fire frequency, and probability will cause decreases in biomass across the island forests; selection of fire tolerant species and options to reduce fire susceptibility should be considered by forestry managers
- if fires increase within the Island Forests to 5.5 times historical area burned, trees will likely be extirpated from this landscape; management of fire in the forest at this level will be near impossible
- hardwood species are most likely to dominate under future climate regimes; forest managers should consider how they might manage a forest dominated by aspen and balsam poplar
- forest managers should likely expect declines and biomass for all ecoregions

However, there is one last note of caution for all users of this report. Some of the changes in species composition do not appear to be reasonable. For example, the complete loss of many species on the landscape, such as white spruce, black spruce, and balsam fir is unlikely. As stated earlier, all models produce a generalized output of what a potential future of the landscape might look like given model constraints. It isn't likely that white spruce, black spruce and balsam fir will be totally eliminated from the landscape, but will perhaps appear in much lower numbers than currently. ArborVitae Environmental Services and KBM Forestry Consultants Inc. (2006) suggest that the nature of changes in species composition suggested by the model may have some general characteristics:

- The proportional decline in abundance estimated by the model, compared with the current forest, was greatest for those species with low initial abundance and least for those species that were widely present; and
- The abundance of species with low initial abundance levels declined to zero;

Both of these effects noted by ArborVitae Environmental Services and KBM Forestry Consultants Inc. (2006) were apparent in this report as well. As with all modeling endeavours, lessons learned are usually in the form of generalities and not absolutes and that is what is hopefully represented in this paper.

## LANDIS-II limitations

LANDIS-II is a powerful tool for examining multiple interacting ecological processes operating at broad spatial and temporal scales. These interactions can be of such complexity that predictions of future forest ecosystem states are beyond the analytical capability of the human mind (Gustafson et al. 2011). Unfortunately models are not infallible, and are only a simplified representation of the complexities of nature based on human understanding of these processes. LANDIS is based on current ecological knowledge and theory; this is both a blessing and a curse (Gustafson et al. 2011). Models are reliable when they have robustly encapsulated the conceptual models derived from ecological theory; however, currently theory and knowledge is subject to falsification as the scientific enterprise pushes back the frontiers of ignorance (Gustafson et al. 2011). Therefore, it is important to recognize the abilities of the model being used (positives discussed in previous sections) and note its limitations, especially when analyzing results. The following sections will deal with the few limitations of the LANDIS-II model that should be noted before using it in research and application of results.

### *Data intensive*

LANDIS-II requires very detailed information about various ecosystem properties at relatively high spatial resolution and extent (Gustafson et al. 2011). This is often quite difficult to obtain, and frequently the modeler is forced to resort to best estimates to fill in any blanks. Although obtaining the knowledge can be quite difficult, the large amount of data required to run the model also takes a long time to process and prepare for use in the model. On the output side, LANDIS-II produces a variety of maps showing changes on the landscape. While maps are a great tool for displaying changes on the landscape, they are more difficult to deal with when each extension (age class, fire severity, biomass, etc.) produces a total of 500+ maps. These maps become cumbersome to deal with and most of them must be processed through a geographical information system (such as ArcGIS) to analyze information.

### *Steep learning curve*

LANDIS-II was initially developed as a scientific research tool and therefore explicit design and development of a user interface and application protocols has not been done due to expense (Gustafson et al. 2011). This makes it challenging for non-modelers to use and requires a steep learning curve for anyone starting to use this model for the first time.

### *Unable to model grasses*

LANDIS-II is specifically designed to model trees on the landscape. This means that grasses, shrubs, and other understory plants are not well represented in the model. This was one of the largest drawbacks because in many studies the southern edge of the boreal forest is predicted to shift northwards and be replaced by grasslands (Hogg and Hurdle 1995, Camill and Clark 2000, PARC 2010). The model would be much more powerful if it could show the competition dynamics between grasslands and forests at an ecotone boundary. These areas are especially important under climate change and this was one question that would be very important to answer with regards to the Island Forests: will it even exist under a warmer future climate?

### *Climate change*

Although the LANDIS-II model is able to produce outcomes with climate change effects, this effect is not available in all modules. For example, the PnET-II for LANDIS-II model allows for the analysis of climate change by adjusting SEP and ANPP. However, the Base Fire Model has uses an entirely different set of inputs derived by the user to demonstrate climate change on the landscape. This can cause much additional uncertainty, there needs to be a more comprehensive way to address climate change. It would be far more useful if the core model within LANDIS-II was able to deal with climatic changes over time and the rest of the models read the information needed from the core processes.

### *Impacts of drought on tree mortality*

Trees age over time within LANDIS-II and eventually die as they reach their maximum longevity. Disturbances such as fire or insects also have to ability to kill tree cohorts in the model. However, the impact of drought on tree mortality is very difficult to model, but is a question of great interest, especially for the Prairie Provinces. There is currently an absence of physiological understanding of tree mortality mechanisms which limits the ability of current models to predict drought induced mortality in trees (Wang et al. 2012). Overall, drought mortality mechanisms are generally not incorporated in large scale dynamic vegetation models like LANDIS. Most large scale vegetation models require some simplification of the plants which causes problems when attempting to simulate drought-induced tree mortality at a large scale(Wang et al. 2012). Drought is an especially prominent issue in the Prairies as moisture limitation is often what delineates the boreal forest from the parkland and grassland regions. The ability to predict the impact of increased droughts on tree survivability and mortality is a key component to understanding the complete picture of the impacts and vulnerability to climate change for this region. There is currently some work underway looking at a way to model the impacts of drought effects on tree mortality using a relationship between moisture and growth rate and simulating mortality when growth drops below a certain threshold (Gustafson 2011). This new module may be able to provide a solution to this issue in the future.

### *Gaps in knowledge*

There are a few areas noted within this report where there were gaps in knowledge and they will be summarized in this section.

First, an assessment of risk was not included in the vulnerability assessment. A risk assessment is a qualitative exercise based on best available professional knowledge and needs to be done by the organization with access to financial records and inner workings of the organization. This step should be done by the organization, but can also be done by a technical team using a workshop format and including stakeholders if the organization is willing to share financial information. The point of a risk assessment is to help decision-makers determine how climate change could affect the ability to achieve outcomes and help understand where to focus adaptation investments and priorities (Sustainable Resource Development 2010). However, the difficulty that comes with risk assessment is that it is completely qualitative, and therefore, may contain some personal biases. It can also be challenging because probability and damages are not always numerically measurable or even available in the early

phases of development (Elahi et al. 2001). A risk assessment would be a complementary follow up after this report, once potential adaptation options have been established.

Second, local knowledge for tamarack and some parameters for other species were missing or incomplete. In areas where only some of the values were missing for a particular species, they could be estimated from plant functional types or similar types of species. The greatest issue occurred with tamarack which is a very individual tree and does not really fit into the broadleaf deciduous tree or needle-leaf coniferous tree category. Tamarack is a coniferous tree; however, it is not evergreen like most conifers. Instead its needle-like leaves turn bright yellow and fall in the autumn. There were very few parameters for this species and it was difficult to estimate many of its properties in PnET-II due to its dual nature. Therefore, this species was dropped from the modeling portion of this study as proper values and calibrations were unable to be completed. This species was not very prominent on the landscape and therefore will not cause a great deal of discrepancy when comparing actual and modeled values.

## Potential future work

Future studies in this region can expand on many aspects of this of this report as there are many areas that could use additional investigation. Foremost, a more detailed examination of the range of climate change predictions should be assessed. Uncertainties will remain inherent in predicting future climate change, even though some uncertainties will likely be narrowed over time. Consequently, it is important to always consider a wide representation of the cascade of uncertainty when conducting an impact assessment. This can be done through the consultation of a wide range of climate and emission scenarios (IPCC 2001a). The fact that only a single climate change scenario was used in this assessment is one greatest faults of this report. Box 1 below shows an example of potential future scenario development giving a more complete examination of future climate change impacts. Given more time and resources these multiple scenarios could be examined.

Replacement of the Base Fire model with the Dynamic Fire model, with comparisons between the two models could be performed. The Dynamic Fire model is far more complex than the Base Fire model because the Dynamic model includes up to 100 different fuel types (such as the Canadian Forest Fire Prediction system), and allows dynamic interactions among fire, vegetation, climate, wind, and landscape structure to incorporate realistic fire characteristics (shapes, distributions, and effects) (Sturtevant et al. 2009). The Dynamic Fire model may be better suited for implementation of climate change effects on future fire due to its ability to provide feedback between fuel types and fire behavior. The Base Fire model is far more simplistic and uses only mean, max, min fire sizes, plus an ignition probability and k value to calculate fire on the landscape. This means that the Base Fire model is not actually linked to climate, the modeler must choose how to represent future fire dynamics on the landscape. It would be interesting to compare both fire models and see whether there is significant difference between fire dynamics and area burned under climate change scenarios.

As noted in the vulnerability assessment, pests and diseases are present within the Island Forests. This was one area which was not included in the modeling assessment that may have a large impact on the future forest. With the prominence of Dwarf Mistletoe in the majority of jack pine stands and the threat

of invasive future species like Mountain Pine Beetle, the effects of pests on the Island Forests should be examined in greater detail. LANDIS-II has a module called the Biological Disturbance Agent which adds insects and disease impacts on the landscape. This extension could be implemented to take into account the effects of pests under climate change and provide a more robust vulnerability assessment with regards to insects and diseases.

Another interesting approach that could be taken is to look at different elements of timber harvesting and how effective they may be in incorporating climate change adaptation options. LANDIS-II has a Base Harvest add-on that allows the user to implement different types of harvesting and management on the forest. This module is unique because it allows modeling of harvesting prescriptions and includes a human element on the landscape that can be used to examine different types of adaptation initiatives to determine the best management practices to reduce vulnerability. This is the only module that contains a human component whereby managers can have a direct impact on the landscape. This would be a great tool for incorporating climate change adaptation initiatives on the landscape with forest management in order to measure the effectiveness of a timber-harvest adaptation to climate change. Different types of harvesting methods could be compared, such as, decreasing rotation lengths or removal of certain types of trees. LANDIS is well suited for evaluating alternative potential solutions to complex management problems such as: evaluating the effectiveness of alternative fire mitigation strategies (Gustafson et al. 2011).

Lastly, LANDIS-II has the ability to simulate landscape dynamics over millions of hectares. All of this work could be expanded upon to encompass the southern boreal forest fringe across Saskatchewan, Alberta, and Manitoba, or even the entire western boreal forest in Canada. This work is scalable up to many different levels of forestry management and can be used to answer a wide variety of forest management questions with regards to climate change adaptation.

### Box 1: Potential future work on climate change scenarios

Historical and future climate change inputs for PnET-II can be obtained from the Canadian Forest Service which produces a suite of downscaled climate scenarios in collaboration with the US Department of Agriculture. Each scenario is derived from a simulation carried out with a state-of-art general circulation model (GCM) (Price et al. 2011). Three GCMs and five emission scenarios were chosen in this example to give a range of future representations covering a wide range of temperature and moisture extremes (Figure 34 and Table 19). The following three GCMs were chosen based on availability of data and their reputation in the global GCM community: the Third Generation Coupled Global Climate Model, version 3.1, medium resolution (CGCM3.1 mr), developed by the Canadian Center for Climate Modeling and Analysis; the Australian Commonwealth Scientific and Industrial Research Organization's Mark 3.5 Climate System Model (CSIROMK35); and the Community Climate System Model, version 3.0 (NCARCCSM3) developed by the US National Center for Atmospheric Research (Price et al. 2011). Climate data was normalized and input to the ANUSPLIN software (Hutchinson et al. 2009) to give a two-dimensional spline 'surface' function that was used to create gridded data sets across North America (Price et al. 2011). Downscaled data at 1 km<sup>2</sup> resolution was obtained specifically for the area surrounding the Island Forests. The coordinates are as follows:

NW Corner – W 106°36'45" N 53°39'39"

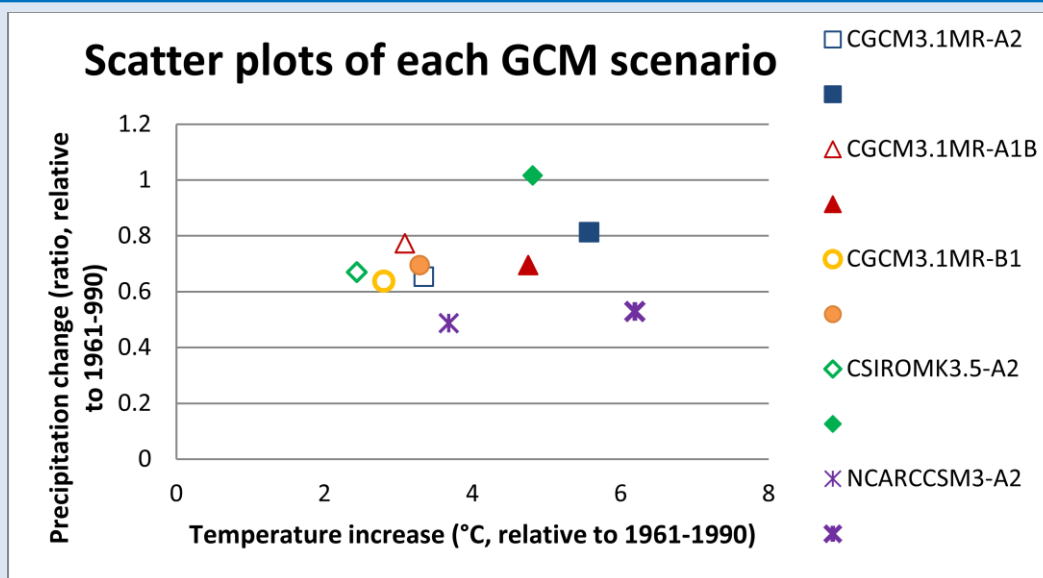
SW Corner – W 106°36'45" N 52°49'57"

NE Corner – W 103°55'30" N 53°39'39"

SE Corner – W 103°55'30" N 52°49'57"

The scatter plot (Figure 34) shows changes in annual mean daily minimum temperature and precipitation ratio for 20 year periods centered on 2050 and 2090, relative to the 1961-1990 baseline (Price et al. 2011). Trends among the GCM scenarios show that projected warming is greater for the 2090s than for the 2050s, but with larger divergence among the GCMs. Specifically, the A2 scenario created greater warming than the A1B, which in turn produced greater warming than the B1 scenario.





**Figure 34: Scatter plot showing changes in annual mean daily minimum temperature and annual precipitation ratio projected by each general circulation model, as forced by each greenhouse gas emissions scenario, relative to means for 1961-1990.** Open symbols represent mean changes for 2040-2059, and closed symbols represent mean changes for 2080-2099. Each scatter plot shows area-weighted means for the Boreal Transition zone in Canada where the Island Forests are located. (Data in figure obtained from Price et al., 2011).

**Table 19: Climate change scenarios**

Climate Model	Scenario	Temperature increase by 2100 relative to 1961-1990	Precipitation change by 2100 relative to 1961-1990
CGCM 3.1 mr	A2	5.575	0.813
CGCM 3.1 mr	B1	3.286	0.694
CGCM 3.1 mr	A1B	4.755	0.694
CSIRO Mk 3.5	A2	4.816	1.016
NCAR CCSM 3.0	A2	6.194	0.528

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