Oil Sands Terrestrial Habitat and Risk Modelling for Disturbance and Reclamation – Phase II Report

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Oil Sands Research and
Information Network

Oil Sands Research and Information Network

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OSRIN provides:

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REPORT SUMMARY

The overall objective of this project is to develop a framework that integrates risk management and strategic decision-making to evaluate the impact of disturbance (natural and industrial) on ecosystem products and services, and on habitat availability for terrestrial species in Alberta's Lower Athabasca planning region. This includes an evaluation of the impact of disturbance, conservation, and reclamation activities associated with oil sands development both at the lease and regional levels. The principal objective in Phase II is an evaluation of the impact of climate and climate change on reclamation success, as compared to the basecase analysis (no climate-related impacts) conducted in Phase I.

Chapter 2, describes the calibration and testing of a tree ring model for the three major tree species represented in the Alberta Oil Sands region, white spruce (*Picea glauca*), trembling aspen (*Populus tremuloides*) and jack pine (*Pinus banksiana*). The model simulates the relationship between annual sapwood production (expressed as a ring width index), mean daily temperature and available soil moisture. Simulated ring width increments were regressed against the measured annual ring width index to evaluate the performance of the model. The tree ring model was able to successfully predict patterns in ring chronologies for white spruce and jack pine. Indeed, the explanatory capability of the model exceeded that which is typical from studies linking ring width to simple climate variables. In the case of aspen, results were less definitive. This study thus provides evidence for the applicability of this approach and it also highlights the utility of incorporating a few basic ecophysiological principles into models of tree growth.

Chapter 3 describes the characteristics of five Global Circulation Models and the Alberta Climate Model that are used to simulate climate change in the rest of the report.

In Chapter 4, the Tree and Climate Assessment (TACA) model is used to assess the regeneration potential of three boreal tree species (white spruce *Picea glauca*, trembling aspen *Populus tremuloides* and jack pine *Pinus banksiana*) on different soil types in northern Alberta. Model results indicate that under most scenarios, regeneration by all species is generally favoured by the warmer temperatures and higher annual precipitation predicted under climate change. One striking exception is the most severe emission scenario, where very warm conditions are a significant driver of moisture limitations and a low to non-existent regeneration potential. In the case of aspen, its ability to reproduce vegetatively improves the adaptive capacity of this species; clones can regenerate and persist by re-sprouting while maintaining their colonizing ability and potentially enhancing their distribution through seed-based regeneration. As a model that incorporates many of the biophysical variables important to tree regeneration, TACA is a suitable tool for making realistic projections of the impact of climate and climate change on the regeneration potential of the boreal tree species in northern Alberta.

Chapter 5 evaluates future ecosystem development in jack pine, aspen and white spruce with the FORECAST Climate model after incorporating the five climate change scenarios developed in Chapter 3. Stands initiated under current climatic conditions (in year 2011) are predicted to experience enhanced long-term productivity (to year 2111) under a changing climate regime, as compared with the growth that would have occurred if historical climatic conditions been

maintained over the next 100 years. Although there was a substantial range among GCM scenarios in their projections of stemwood growth, the minimum projection was always greater than that derived from the historical climate data. In general, forest productivity in northern latitudes is temperature-limited. Model output suggests that tree productivity in the region may be enhanced through much of the 21st century as a result of improvement in the thermal regime (longer growing seasons, warmer soil, increased decomposition) and potentially an overall increase in available moisture, that more than compensates for any negative impact associated with growing season moisture limitations. In general, understory plant communities were negatively affected by the projected increase in overstory productivity under climate change.

Model projections indicated that habitat suitability under climate change would be improved overall, relative to values derived using the historical climate regime. The greatest improvement was for the d1 (aspen) ecosite and the least in the d3 (white spruce) ecosite.

Taken together, the model results suggest a number of management responses within the context of oil sands reclamation that can reduce risk, and help mitigate carbon emissions and retain habitat features, at least for some species. These are:

1. **Minimize the forest cover removed as part of mine operations.** Retention of forest cover improves the carbon balance and, depending on its areal extent and spatial configuration, can also serve as refugia for wildlife on the mine footprint.
2. **Return forest cover as soon as is practicable.** Forest productivity under climate change is enhanced, which will translate into higher carbon sequestration and improved habitat suitability as compared to the reference case (the historical climate regime). Returning forest cover quickly thus serves to leverage the benefits from improved productivity.
3. **Expand forest carbon sinks to promote carbon storage and development of habitat attributes.** Adding fertilizer annually for 5 to 10 years after planting, particularly on poor sites, will promote both tree and understory productivity, and thus carbon storage and development of habitat attributes. Retaining and adding slash and other dead organic matter after land clearing will also increase carbon stores (at least temporarily) but more importantly create valuable habitat.
4. **Encourage species mixtures over monoculture plantations.** Conifer monocultures and extensive tracts of aspen-dominated forests are vulnerable to outbreaks of insect defoliation and bark beetles. Planting tree species in mixtures or at the very least, reducing the areal extent of monocultures may help mitigate risk, enhance forest resilience, and/or prevent large-scale pathogen outbreaks.
5. **Increase protection measures.** Mine operators should develop and implement regular monitoring programs on their reclaimed areas to identify potential threats to stand health before they become unmanageable.
6. **Enhance fire suppression capability.** An increased risk of forest fires (both in frequency and severity) is predicted to occur with climate change. This could result

in significantly greater releases of carbon as material is consumed, but can also generate rapid and pronounced shifts in community composition.

ACKNOWLEDGEMENTS

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1 INTRODUCTION

The overall objective of this project is to develop a framework that integrates risk management and strategic decision-making to evaluate the impact of disturbance (natural and industrial) on ecosystem products and services, and on habitat availability for terrestrial species in Alberta's Lower Athabasca planning region. This includes an evaluation of the impact of disturbance, conservation, and reclamation activities associated with oil sands development both at the lease and regional levels.

A comprehensive overview of the project is provided in the document entitled Oil Sands Terrestrial Habitat and Risk Modelling for Disturbance and Reclamation, submitted to the Oil Sands Environmental Management Division, of Alberta Environment. The project will be conducted in three phases.

The Phase I work consisted of three principal activities described in detail in three linked reports under the broad title Oil Sands Terrestrial Habitat and Risk Modelling for Disturbance and Reclamation Phase I[1]. The activities included:

1. A dendrochronology study that examined the relationship between climate and tree growth (specifically ring width) for four species (white spruce *Picea glauca*, black spruce *Picea mariana*, jack pine *Pinus banksiana*, and trembling aspen *Populus tremuloides*) in the sub-boreal forests of western Canada (Alberta and Saskatchewan).
2. A habitat suitability analysis for ten boreal forest wildlife species (moose, black bear, snowshoe hare, lynx, red-backed vole, fisher, Cape May warbler, ruffed grouse, pileated woodpecker, and northern goshawk) in natural forests and within reclamation plans developed as part of the Kearl Lake mine[2]. Input values for each index were derived from output generated from the ecosystem simulation model, FORECAST.
3. A risk analysis of the potential development of water stress in young reclamation plantations consisting of white spruce, trembling aspen, and jack pine established on different ecosites as a function of soil texture and slope position.

The principal objective in Phase II is an evaluation of the impact of climate and climate change on reclamation success, as compared to the basecase analysis (no climate-related impacts) conducted in Phase I. This report details activities completed in Phase II within the March 31, 2010 to March 31, 2011 fiscal period.

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[1] See Welham, C., 2010. *Oil Sands Terrestrial Habitat and Risk Modeling for Disturbance and Reclamation – Phase I Report*. OSRIN Report No. TR-8. 109 pp.

[2] Imperial Oil Resources Ventures Limited Kearl Oil Sands Mine Project - http://www.imperialoil.ca/Canada-English/operations_sands_kearl.aspx

The potential effect of different climate change scenarios on growth and mortality in reclamation areas was projected using the FORECAST Climate model and associated modelling tools to evaluate their combined impacts on overall ecosystem development in a risk assessment context. As in Phase I, the Kearl Lake mine development plan was used as the test case.

Activities in Phase II were scheduled to occur in five parts (see Figure 1). Due to limitations imposed by the timing of available funding and logistical issues associated with the incorporation of climate change variables into simulation exercises, not all objectives were completed as planned. Details are provided in each of the subsequent chapters.

The basic approach was to explore climate impacts on key components of the reclamation 'cycle'. In parts 1 to 3, the potential impact of different climate change scenarios on regeneration and moisture stress in reclaimed areas was projected. Specifically, in Part 1, a sapwood growth submodel was used to project annual stemwood increment for jack pine, aspen, and white spruce on sites representative of the Kearl Lake reclamation landscape using daily historical climate data from the Fort McMurray region. These sapwood increment projections were compared against selected tree ring chronologies derived from the Phase I work. This exercise constitutes a means for 'testing' the hypothesized relationships between climate and ring growth and for developing a clearer understanding of the interaction between phenology (i.e., when carbohydrate production switches between growth and storage) and climate. It thus provides a method for calibrating FORECAST Climate's projections of net primary productivity in terms of patterns in ring growth. In Part 2, six greenhouse gas emission scenarios used by Barrow and Yu (2005) in their climate change projections for Alberta were compiled and downscaled for use in subsequent analyses. The Tree and Climate Assessment (TACA) model was employed in Part 3 to evaluate how regeneration success on a given reclaimed ecosite might be affected by climate change. The focus of Part 4 was to evaluate future ecosystem development using the FORECAST Climate model within the context of the climate change scenarios derived in Part 2. This exercise projects the long-term productivity and development of structural and ecosystem attributes for different ecosites within the Kearl Lake mine reclamation area.

A proposed spatial analysis of indices of habitat suitability for the Kearl Lake mine development plan was not completed, nor was it possible to provide a detailed, 3-dimensional visual representation of the temporal and spatial development of plantations within a subsection of Kearl Lake mine reclamation area (part 5). These activities are planned for completion in the next funding cycle.

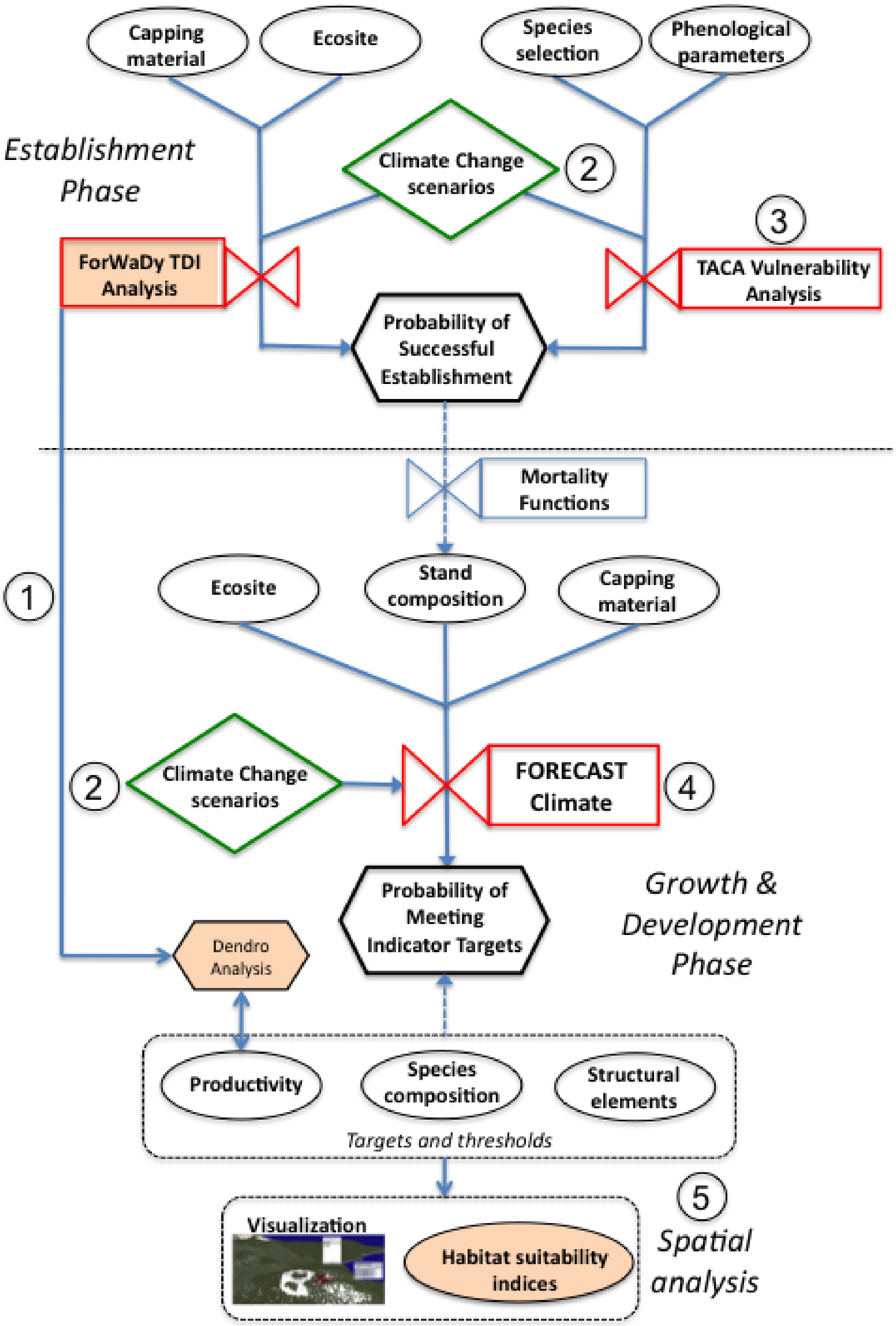

Figure 1. Schematic illustration of Phase II activities.
Numbers refer to component parts (see text for further details).

2 EVALUATION OF A TREE-RING MODEL USING DATA FROM SELECTED SITES IN BOREAL ALBERTA

This chapter describes the process of calibrating and testing a tree ring model for the three major tree species represented in the Alberta Oil Sands region, white spruce (*Picea glauca*), trembling aspen (*Populus tremuloides*) and jack pine (*Pinus banksiana*). The model simulates the relationship between annual sapwood production (expressed as a ring width index), mean daily temperature and available soil moisture, for jack pine, white spruce, and trembling aspen. Simulated ring width increments were regressed against the measured annual ring width index to evaluate the performance of the model.

The tree ring model was able to successfully predict patterns in ring chronologies for white spruce and jack pine. Indeed, the explanatory capability of the model exceeded that which is typical from studies linking ring width to simple climate variables. In the case of aspen, results were less definitive. The model generated poor results in stands from one region (High Level) but was more successful in another (Calling Lake). Although defoliation events can have a significant impact on ring width in aspen (in addition to climate), across the three species the model was capable of simulating the relationship between climate and patterns of ring growth. This study thus provides evidence for the applicability of this approach and it also highlights the utility of incorporating a few basic ecophysiological principles into models of tree growth.

2.1 Introduction

Many dendrochronological studies have been conducted on the empirical correlation between ring width and environmental factors. This is in large part because the traditional focus of dendrochronology has been to link climate variables with tree ring chronologies to predict historical trends in climate (Fritts 1976). Developing a mechanistic physiologically based model of plant secondary growth (Rocha et al. 2006), however, would allow for construction of testable hypotheses and provide a means by which plant response (i.e., ring width) could be predicted from one or more climate variables. Challenges to the latter approach include uncertainties about what controls plant carbon allocation (Wardlaw 1990) and how the physical and chemical environments interact with plant physiological and biochemical processes (Fritts 1976). The few dendrochronological studies that have explored the mechanistic basis of ring width typically assume that photosynthesis is its primary determinant (Gower et al. 1995, Pietarinen et al. 1982, Rocha et al. 2006). As noted above, however, ring growth in any given year is the result of a series of complex physiological process, much of which is not well understood (Cannell and Dewar 1994, Gower et al. 1995, Kozlowski et al. 1991). In addition, current ring growth can be at least partly influenced by the prior environmental conditions that occurred weeks, months, or even years previously (Arneth et al. 1998, Gough et al. 2008, Lo et al. 2010, Sampson et al. 2001).

Tree rings are also useful as a proxy for overall tree growth. While there are some limitations in extrapolating from ring width (e.g., Bouriaud et al. 2005), the strong positive relationship between cambial production (ring width) and tree productivity is widely recognized (Cook and Kairiukstis 1990, Fritts 1976). The strength of this relationship is supported by the generally good correlations between measures of net ecosystem production (NEP) from eddy covariance techniques and biometric measurements of woody tissue increments (Gough et al. 2008, Ohtsuka et al. 2009). Given the strength of these relationships, there is considerable interest in predicting how ring width might be expected to change in relation to predicted shifts in the climate regime (Lo et al. 2010). One complicating factor is that photosynthesis and ring growth are often only weakly correlated (Gough et al. 2008). This is because photosynthate production can also be allocated to storage (rather than growth), at least at certain times of the year, and this stored carbon is used to initiate growth during the next growing season (prior to leaf flush; Arneth et al. 1998, Barford et al. 2001, Sampson et al. 2001). There is evidence, for example, that stored labile C is critical to loblolly pine (*Pinus taeda* L.) growth during the early growing season (Sampson et al. 2001), and that starch accumulation by sugar maple in late summer is strongly correlated to early spring growth in the following season (Wong et al. 2003). Seasonal variability in tree ring carbon isotopic ratios also suggests a reliance of early season growth on stored carbohydrates (Helle and Schleser 2004).

In temperate zone tree species, stored carbon is allocated either to bud and leaf initiation or the production of sapwood (known as early wood). The latter is responsible for initiation of that year's stem diameter growth and thus is recorded as part of the annual tree ring increment. After leaves are fully flushed, trees continue to allocate production to cambial growth (new sapwood) until the latter half of the growing season when further production is allocated to storage (Coder 1999). For example, Gough et al. (2008) reported that growth in the spring preceded positive net canopy carbon uptake by ~2 to 3 weeks and more than 25% of annual carbon assimilation occurred after growth had effectively ceased in the autumn. Carbon assimilated late in the growing season was thus allocated to early-season growth the following year (Barford et al. 2001).

One aspect of forest ecosystems that is particularly sensitive to climatic variability is soil moisture, both in terms of its direct impact on tree growth and, indirectly, via regulation of soil processes (e.g., organic matter decomposition). A number of forest growth models include soil moisture and/or precipitation in their calculation of forest production (see Dixon et al. 1990 for examples). One example is the FORECAST Climate model (Kimmins et al. 2010). This model has a comprehensive representation of water balance (i.e., inputs from precipitation, snow, interflow, canopy through-fall etc., and losses from evaporation, transpiration, percolation) in multiple soil layers (including reclamation materials), competition for water, and moisture deficit. FORECAST Climate is one of the few models that can also simulate the effect of stand management or natural disturbance on forest hydrology. A key feature of FORECAST Climate is a submodel that integrates climate variables (moisture and temperature) with annual net primary productivity, and which is then allocated among sapwood production (and other biomass components) and storage (to fuel production at the beginning of the next growing season). This chapter describes the process of calibrating and testing the tree ring model for the three major tree species represented in the Alberta Oil Sands region, white spruce (*Picea glauca*), trembling aspen (*Populus tremuloides*) and jack pine (*Pinus banksiana*). This is a necessary step for its inclusion within FORECAST Climate, the latter of which will be used for further simulation work within the Phase II project.

2.2 Materials and Methods

2.2.1 *The Tree Ring Model*

A schematic illustration of the tree ring submodel is shown in Figure 2. Stored carbohydrates from the previous season are used at the start of each growing season to fuel NPP, a proportion of which is allocated to sapwood production. Air temperature and a simulated Transpiration Deficit Index (TDI) then drive subsequent NPP within the current growth season. Further details of their calculation are provided below. The model uses a heat sum threshold to determine the point at which allocation is shifted from sapwood production to storage for the following year. The relative annual sapwood increment is then compared directly to measurements of ring width index.

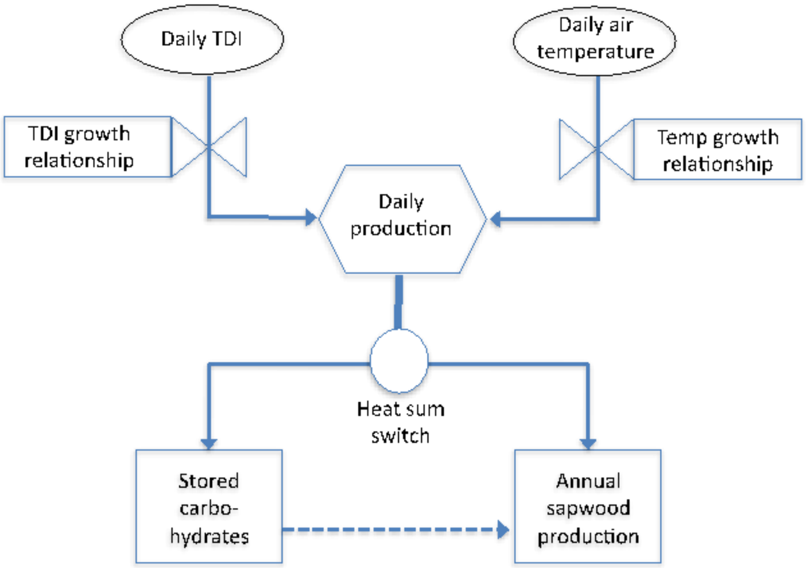

Figure 2. An illustration of the tree ring model used in FORECAST Climate. Daily production is allocated either to stored carbohydrates or annual sapwood production. The dashed arrow connecting stored carbohydrates to annual sapwood production indicates that, at the start of every growing season, stored carbohydrates from the previous season are used to fuel initial annual sapwood production.

2.2.2 *Model Calibration*

2.2.2.1 Air Temperature, Precipitation and Radiation

Historical climatic data were obtained from Canada's National Climate Archive (http://www.climate.weatheroffice.ec.gc.ca), for three locations in the boreal mixedwood region of northern Alberta (Table 1).

Table 1. Weather stations used in this study.

Station	**Altitude**	**Latitude**	**Longitude**	**Average annual T**	**Average annual P**
	m.a.s.l.			°C	mm
Fort Chipewyan	232.0	58° 46’ N	111° 7’ W	-1.7	367.9
High Level	338.0	58° 37’ N	117° 9’ W	-1.3	394.1
Calling Lake	598.0	55° 15’ N	113° 11’ W	0.9	453.8

2.2.2.2 Calculating the Transpiration Deficit Index

ForWaDy (Forest Water Dynamics; Seely et al. 1997) is a vegetation-oriented, forest hydrology model. It has been evaluated against time-sequence field measured moisture content data from oil sands reclamation covers (Seely at al. 2006). The model can be used as a stand-alone application, and it is integrated within FORECAST Climate where it is coupled to the main tree growth engine and the tree ring model (Kimmins et al. 2010, Seely and Welham 2010).

ForWaDy simulates potential evapotranspiration (PET) using an energy balance approach based on the Priestly-Taylor equation (see Figure 3). Incoming radiation is partitioned among vertically stratified canopy layers (vegetation type) and the forest floor to drive actual evapotranspiration (AET) calculations. The model has a representation of soil physical properties dictating moisture availability, storage, and infiltration, and it simulates the relative impact of soil cover depth, minor vegetation competition and climate on the water availability for trees. A detailed description is provided in Seely et al. (1997, 2006).

Water stress in ForWaDy is calculated as a transpiration deficit index (TDI). In essence, the TDI represents the difference between potential transpiration (as dictated by available energy) and actual transpiration (limited by available moisture), as follows:

$$\text{TDI} = (\text{CanT\_Total} - \text{CanTActual})/\text{CanT\_Total}$$

where:

CanT_Total = energy limited transpiration: f (leaf area index, intercepted short-wave radiation, canopy albedo, and canopy resistance)

CanT_Actual = actual tree transpiration: f (CanT_Total, root occupancy, available soil moisture)

Table 2 provides a listing of the data used to calibrate ForWaDy.

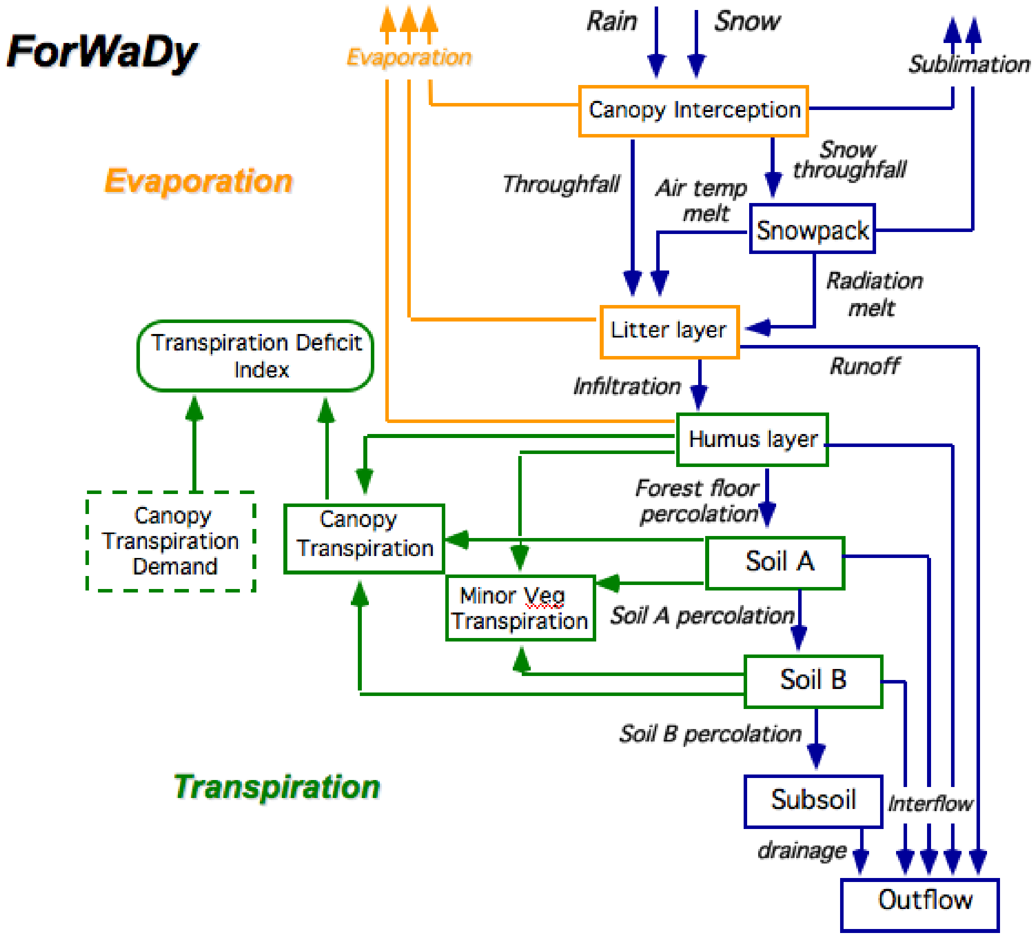

Figure 3. Schematic illustration of the structure of ForWaDy indicating the flow pathways and storage compartments represented in the model.

Table 2. Parameter values used to calibrate ForWaDy model.
Data were obtained from Alberta Environment (2006), Pedocan Land Evaluation Ltd (1993) and Tajek et al. (1989).

Parameter	**White spruce**	**Jack pine**	**Trembling aspen**	
			High Level	Calling Lake
Conifer fraction	1	1	0.4	0.4
Maximum LAI conifer	1.5	1.3	0.5	0.5
Deciduous fraction	0.2	0.2	1	1
Maximum LAI deciduous	1	1	0.95	1
Canopy resistance	0.4	0.4	0.1	0.1

Parameter	**White spruce**	**Jack pine**	**Trembling aspen**	
			High Level	Calling Lake
Maximum understory cover	0.75	0.75	0.65	0.55
Depth horizon H (cm)	15	15	15	10
Depth horizon A (cm)	35	35	35	35
Peat PWP theta[1]	0.17	0.12	0.13	0.13
Peat PWP US theta[1]	0.14	0.14	0.12	0.12
Soil A FC theta[2]	0.28	0.28	0.28	0.28
Soil A PWP theta[1]	0.17	0.15	0.16	0.16
Soil PWP US theta[1]	0.14	0.14	0.14	0.14
Texture horizon A[3]	2	2	3	5
Soil depth at the start (cm)	90	90	60	50
Snow depth at the start (cm)	50	50	30	20
Peat depth at the start (cm)	50	50	40	40
Coarse fraction horizon A	0.30	0.30	0.15	0.25
Coarse fraction horizon B	0.35	0.35	0.25	0.30
Coarse fraction subsoil	0.65	0.65	0.35	0.40
Litter layer depth (cm)	25	25	12	20

[1] PWP theta: soil water potential at which the Permanent Wilting Point occurs.

[2] FC theta: soil water potential at which the Field Capacity occurs.

[3] Textural class for horizon A: sand=1, silt=2, loamy sand=3, sandy loam=4, silt loam=5, loam=6, sandy clay loam=7, silt clay loam=8, clay loam=9, sandy clay=10, silt clay=11, clay=12.

2.2.2.3 Deriving the NPP Multiplier for Mean Daily Air Temperature and TDI

In previous work, Seely and Welham (2010) used an iterative approach to establish the functional relationships between the NPP multiplier, and mean daily temperature and TDI, for jack pine, white spruce and trembling aspen. Stands were located in undisturbed forested areas adjacent to the Syncrude mine site near Mildred Lake from which a series of tree ring chronologies were derived. The model was run iteratively with different combinations of temperature and TDI response curves, and heat sum switch thresholds (see Figure 2), from which annual sapwood production (expressed as a ring width index) was predicted. Simulated annual sapwood production was then regressed against the measured annual ring width index to identify the combinations that provided the best fit for each species. In all cases, the model was able to predict measured annual sapwood production with reasonable accuracy ($r^2 > 0.5$). These coefficients of determination are substantially greater than most published relationships between climate variables and ring width (e.g., Case and Peterson 2005, 2007; Grisbauer and Green 2010; Lo et al. 2010). Since the pattern in ring chronologies was strongly reflective of climate, the temperature and TDI functional relationships were retained and used in the simulations reported here (Figure 4). However, because the ring chronologies used in this study were derived from older stands than used in Seely and Welham (2010), distributed across the boreal mixedwood region of Alberta and with different climate histories (see Table 1), the switching thresholds were re-defined for these populations, as detailed in the next section.

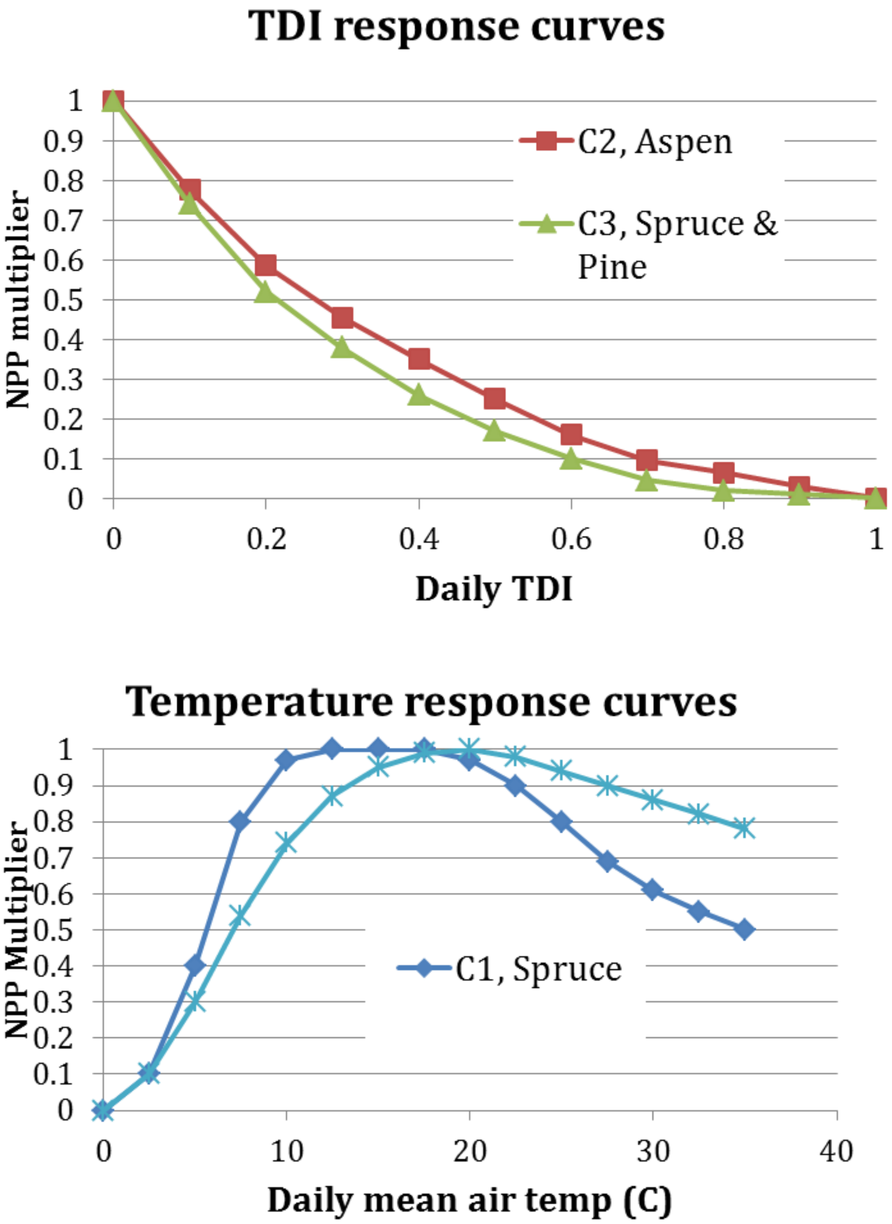

Figure 4. Temperature and TDI response functions (derived from Seely and Welham 2010).

2.2.2.4 Deriving Thresholds for the Heat Sum Switches

Three heat sum thresholds (see Figure 2) were derived from calculations of cumulative degree-days (in °C), using 5 °C as the baseline and 1 January as the starting date. The first threshold is the time when the tree breaks dormancy and stored carbohydrates from the previous season are used to fuel initial annual sapwood production. The second threshold indicates the time when photosynthesis begins, while the third threshold determines when daily production is switched from current-year sapwood growth to carbohydrate storage for use in the next growing season.

To derive the thresholds, the tree ring model was run iteratively for each species with each of the species-specific temperature and TDI response curves, in conjunction with a series of heat sum values corresponding to each of the three switch thresholds. Simulated annual sapwood production (expressed as a simulated annual ring width index; see below) for a given threshold combination was then regressed against the measured annual ring width index to identify the best combinations for the threshold values. The final threshold values are reported in Table 3.

Table 3. Threshold values (accumulated degree-days) for the switch points in carbohydrate allocation.

	White spruce	***Jack pine***	***Trembling aspen***	
Threshold	Fort Chipewyan		High Level	Calling Lake
Break dormancy	75	75	75	75
Photosynthesis	250	250	220	275
Storage	1250	1250	1390	1300

2.2.2.5 Dendrochronological Data

Four published tree ring chronologies were compared with predicted sapwood production, one each for white spruce and jack pine, and two for trembling aspen (Table 4). These measured chronologies were selected as having the most complete ring sequences and their broad geographic range improved the prospects for using samples derived under different climatic conditions.

The annual ring width index for the measured and predicted values was calculated, as follows. Rings derived from trees when they were less than 5 years old (at breast-height age) were excluded. To assure that tree ring dates were correctly assigned and identify years with missing rings, all chronologies from a given species were correlated with each other. A curvilinear function was then fitted to each chronology to remove any age-related trends in ring width (since average ring width tends to decline with age). Next, the average deviation of the measured width from the fitted line for each species was calculated for each year. Each annual deviation was then divided by this average to generate a normalized series of annual ring width indices.

Table 4. Tree-ring records used to evaluate the tree-ring submodel.

ID	**Species**	**Altitude** (m)	**Latitude**		**Longitude**		**Weather station**	**Reference**
CAL	Aspen	630	55°	17‘	112°	58‘	Calling Lake	Hogg et al. (2005)
HIGH	Aspen	340	58°	19‘	117°	14‘	High Level	Hogg et al. (2005)
NOAA 132	Jack pine	-	59°	45‘	112°	12‘	Fort Chipewyan	Larsen (1997)
NOAA 212	White spruce	209	59°	0‘	112°	0‘	Fort Chipewyan	Meko (2006)

2.3 Results and Discussion

2.3.1 *White Spruce*

Overall, the model was successful in simulating the general trends in ring width measured for white spruce (Figure 5). Measured ring widths increased steadily from 1980 to 1989, were reasonably consisted through 1998, and then declined sharply in 1999 and 2000. The latter decline is consistent with trends reported in other regions of Alberta (Sauchyn et al. 2003). Its likely cause is moisture stress. The years 1999 to 2004 marked the worst widespread drought in Canada in the last century (Wheaton et al. 2005), as exemplified by a severe drought index in the Fort McMurray area (Khandekar 2004). The effect of the drought during this period was thus evident in the tree ring model (Figure 5). Evidence suggests that for white spruce, climatic conditions towards the end of the growing season are an important determinant of ring growth in the subsequent year (Fritts 2001, Kozlowski and Pallardy 1997a, Zahner 1968). One possibility is that high late season temperatures increase respiration rates thereby depleting carbohydrates by reducing storage potential (Kozlowski and Pallardy 1997a). However, Chhin et al. (2004) concluded that white spruce is sensitive to climatic fluctuations because growth rates are particularly sensitive to moisture deficiency, which could be exacerbated by elevated evapotranspirational demands at higher temperatures (Kozlowski and Pallardy 1997a).

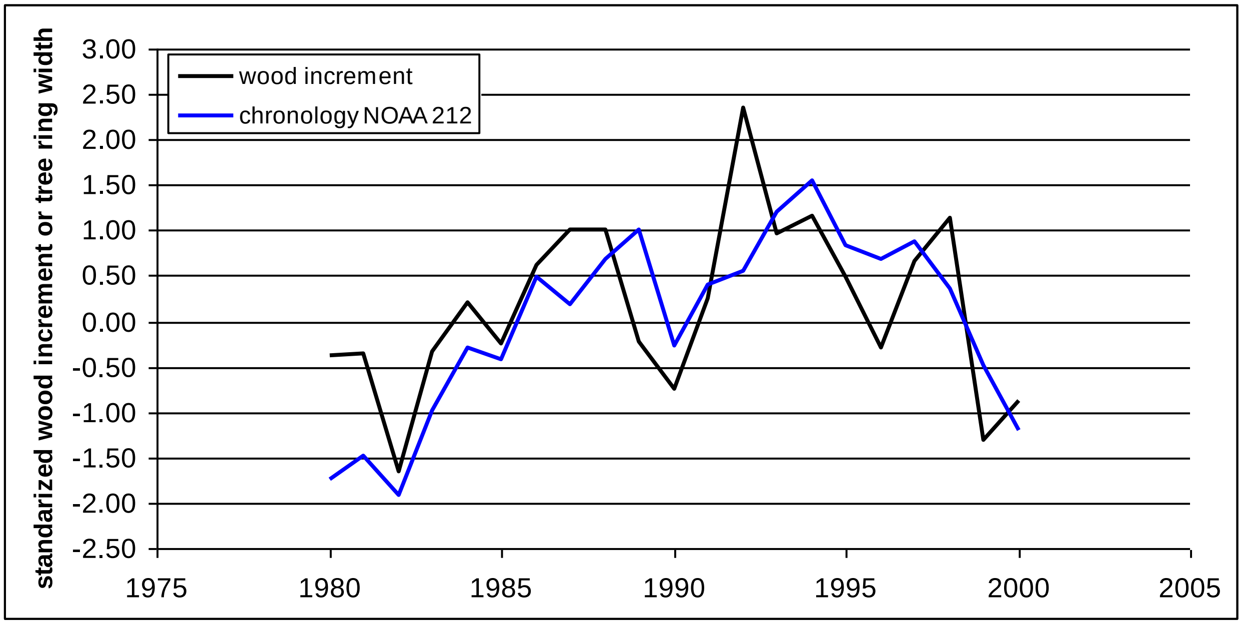

Figure 5. Comparison of the standardized predicted ring index from the model (black line) and the average measured index from the NOAA 212 chronology (blue line; see Table 4) for white spruce.

When the predicted and measure ring indices were compared directly, the tree ring-model accounted for 48% (r = 0.69) of the observed variability in tree ring widths (Figure 6). This value is substantially higher than the correlation coefficients that are typically reported for simple dendroclimatological relationships (r < 0.2; Lo et al. 2010, Rocha et al. 2006, Yu et al. 2007). Thus, the inclusion of ecophysiological factors and climate as represented in the tree ring model provides a promising approach to simulating patterns of ring development in white spruce.

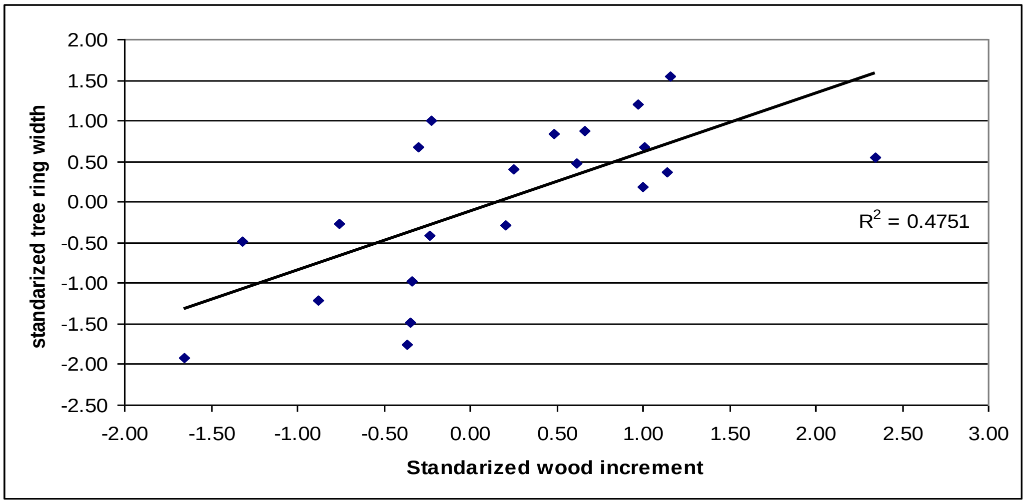

Figure 6. Regression of standardized measured vs. simulated ring width indices for white spruce.

2.3.2 *Jack Pine*

Measured tree ring chronologies for jack pine were shorter than for white spruce, spanning a period of only 11 years (1980 to 1991; Figure 7). Nevertheless, there was considerable variation in ring width during this period that was also reflected in the predictions of the model. In fact, the model predicted ring width patterns in jack pine better than for spruce (cf. Figures 5 and 7), with a coefficient of determination of 57% (versus 48% in spruce).

No published reports are available for jack pine in Alberta describing tree ring relationships with climate. In terms of climate variables, jack pine productivity appears to be positively related to summer precipitation and spring temperatures of current year (Seely and Welham 2010). Brooks et al. (1998) indicated that moisture limits the southern range of jack pine and cold soil temperatures limit the northern extent. That available moisture and air temperature are two key variables in the model could explain its success in predicting patterns in ring chronology (Figure 8). In addition, jack pine typically grows on well-drained, coarse textured soils and moisture would therefore be expected to correlate well with patterns of growth.

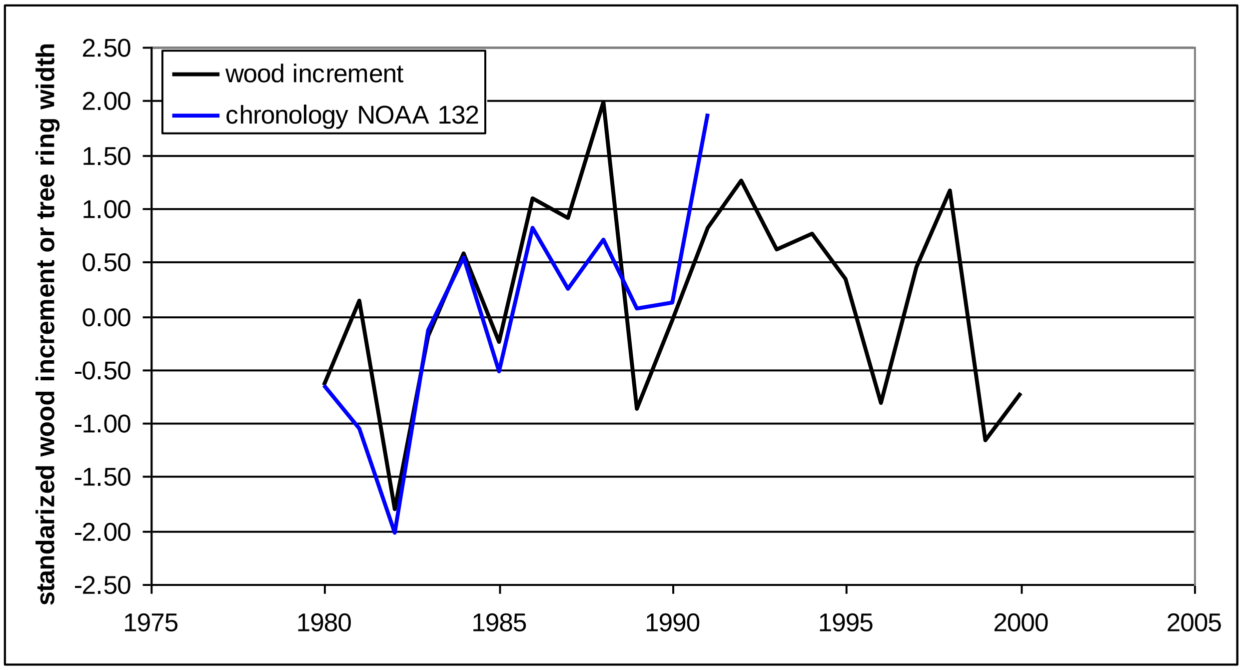

Figure 7. Comparison of the standardized predicted ring index from the model (black line) and the average measured index from the NOAA 132 chronology (blue line; see Table 4) for jack pine.

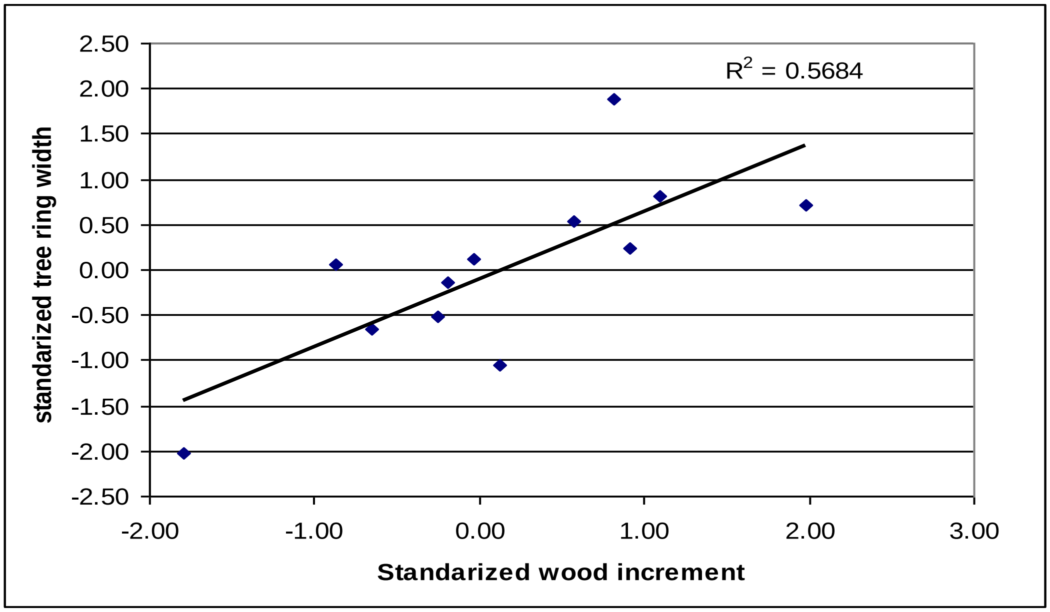

Figure 8. Regression of standardized measured vs. simulated ring width indices for jack pine.

2.3.3 *Trembling Aspen*

Results for trembling aspen were different than the two conifer species. In the High Level chronology, the model had predicted trends in ring width index that were qualitatively similar to the measured indices (Figure 9). The regression analysis, however, indicated that the model explained less than 4% of the variation (Figure 10). Overall, the model tended to either over- or under-predict ring increment.

Results for aspen measured at Calling Lake were mixed. Prior to 1988, the predicted and measured ring chronologies were very different, whereas from 1990 onwards the two lines were similar (Figure 11). Note that 1988 and 1989 were excluded from the analysis due to the presence of “white rings”. White rings are typical of stands subject to insect defoliation events and are characterized by thin cell-walled fibers and an overall decrease in wood density (Hogg et al. 2002, Sutton and Tardif 2005). This disparity in fit between the time periods was also reflected in the regression analysis. When all of the data were included, the model explained less than 8% of the variation (Figure 12). However, when only data from 1990 onwards were regressed, the coefficient of determination increased to 41% (Figure 12).

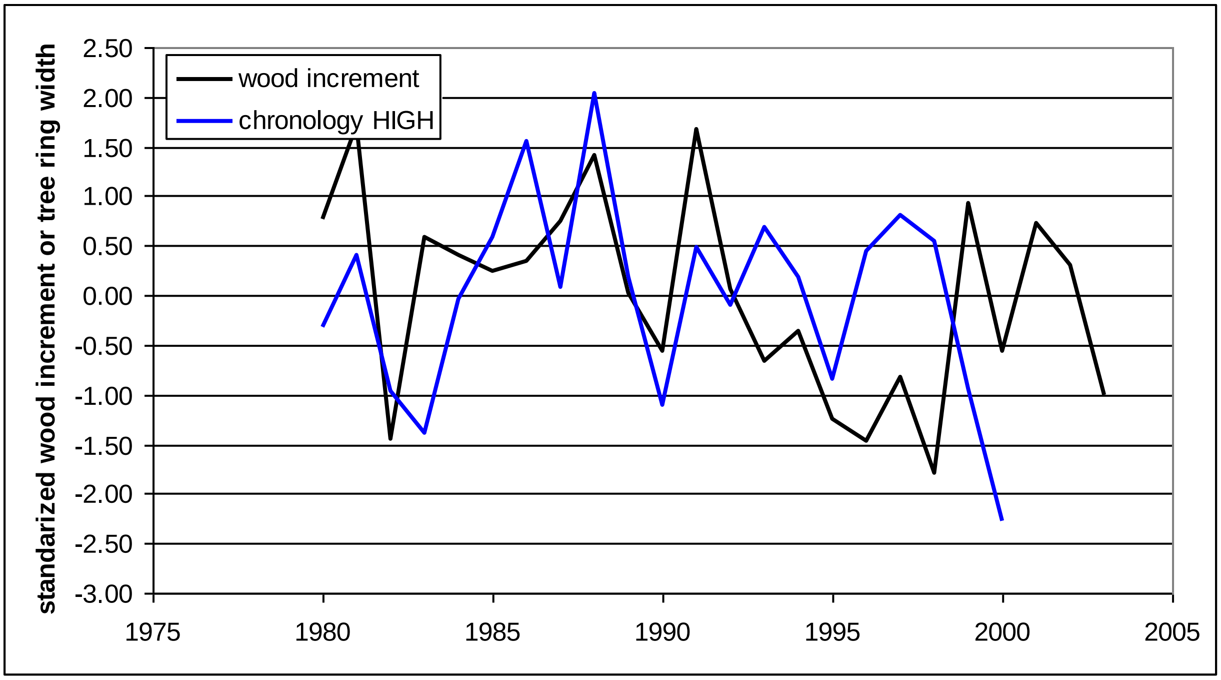

Figure 9. Comparison of the standardized predicted ring index from the model (black line) and the average measured index from the HIGH chronology (blue line; see Table 4) for trembling aspen.

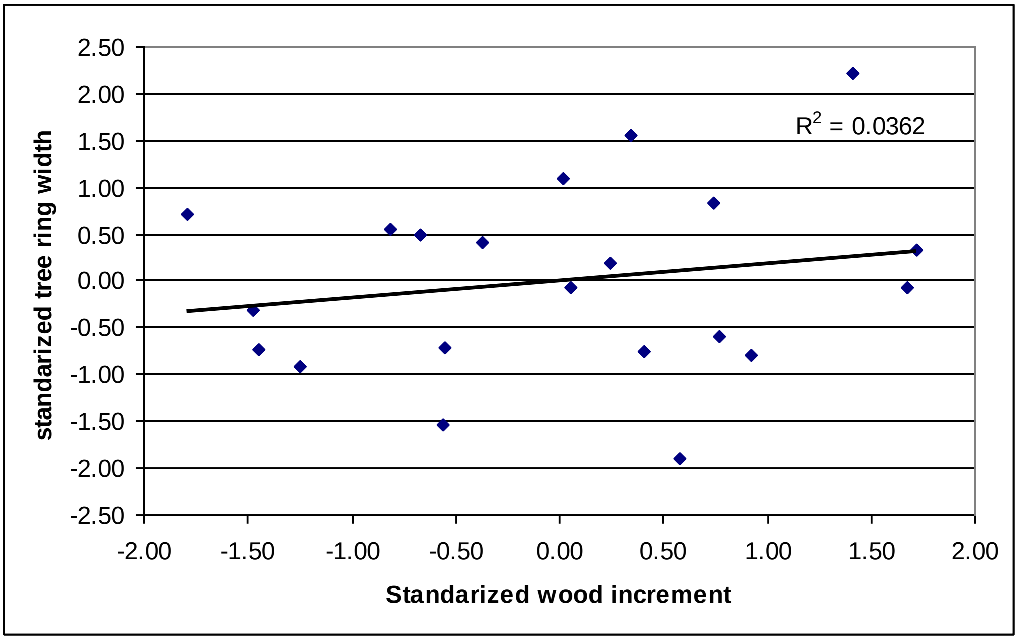

Figure 10. Regression of standardized measured vs. simulated ring width indices for trembling aspen using the HIGH chronology (see Table 4).

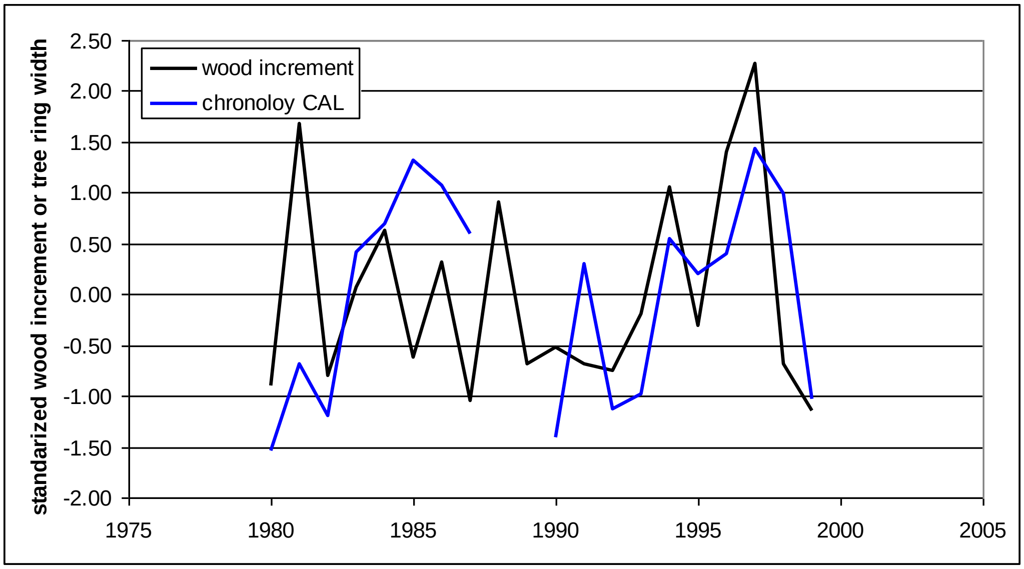

Figure 11. Comparison of the standardized predicted ring index from the model (black line) and the average measured index from the CAL chronology (blue line; see Table 4) for trembling aspen.
The 1988/1989 data gap in measured values (blue line) represents years when white rings were removed (see text).

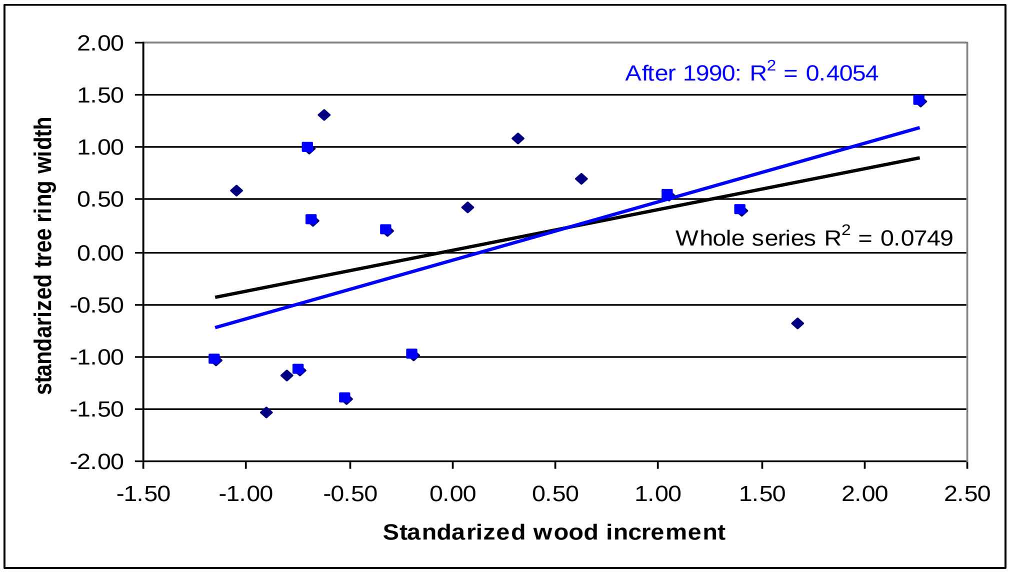

Figure 12. Regression of standardized measured vs. simulated ring width indices for trembling aspen using the CAL chronology (see Table 4).

One explanation for the results is simply that patterns in aspen ring growth are largely unrelated to climate. This seems unlikely. Seely and Welham (2010) obtained a coefficient of determination of 52% for aspen in a dendrochronological analysis similar to that conducted here, though the population was much younger (aged 18 to 36 years). In addition, Hogg et al. (2005) demonstrated that most of the growth variation in populations of aspen across a 30-year period was explained by interannual variation in a climate moisture index in combination with insect defoliation (see below for further discussion of this point). Nevertheless, the relationship between climate variables and aspen growth is not easily defined and this could compromise the predictive capability of the model. For example, high temperatures in spring of the current year have a positive relationship with radial growth (Barr et al. 2007, Hoffer 2007), though high temperatures in the previous summer reportedly are negatively related to ring width (Girardin and Tardiff 2005, Leonelli et al. 2008). In terms of precipitation, higher summer precipitation in the current year is positively related to ring width (Barr et al. 2007, Brandt et al. 2003) but a negative relationship has also been reported (Hoffer 2007, Seely and Welham 2010). Barr et al. (2007) suggested that given the strong link between carbon uptake by boreal deciduous forests in Saskatchewan and spring temperature (see also Baldocchi et al. 2001), it was surprising that the regional scale, tree-ring analysis reported by Hogg et al. (2005) did not included temperature as a key determinant of aspen growth.

The most likely explanation for the poor performance of the model is that, in contrast to the conifer species, these aspen stands were subject to periodic insect defoliation. These events disrupt a tree's photosynthetic capacity and when sufficiently severe result in the reduced ring growth and overall production. Defoliation events were not included in the model. This would not necessarily be problematic if defoliation was correlated directly with climate (as Hogg et al. 2005 suggest). It seems likely, however, that their impact lasts for some period beyond the time of the last event. It may thus take several years for aspen to restore carbohydrate reserves sufficiently to produce a 'normal' ring pattern, depending on the severity and duration of defoliation. One explanation for the strong correlation of aspen ring growth with climate reported by Seely and Welham (2010) then is that the trees in their sample were young enough (aged 18 to 36 years) and sufficiently isolated to not have been exposed to defoliation. Unfortunately, these ideas are not amenable to testing from regional estimates of defoliation. Studies need to be conducted on individual stands with detailed estimates of the severity and duration of defoliation in conjunction with dendrochronology sampling. One simulated defoliation experiment conducted in young aspen trees by Hogg et al. (2002) provides some confirmation of these ideas. They reported that defoliation indeed produced white rings in the current year, and in the year following defoliation tree rings remained narrow (though their appearance and density had returned to normal). Aspen defoliated later in the season formed relatively normal rings, but ring widths were reduced in the subsequent year. Whether, in the Calling Lake sample, trees were largely unaffected by defoliation after 1990 is unknown, but this could explain the better results during the later period.

2.4 Conclusions

The tree ring model was able to successfully predict patterns in ring chronologies for white spruce and jack pine. Seely and Welham (2010) obtained similar results from a smaller, and much younger, sample of trees. Indeed, the explanatory capability of the model exceeded that which is typical from studies linking ring width to simple climate variables (see, for example, Briffa et al. 1990, Girardin et al. 2008, Graumlich 1991, Li et al. 2000, Macías et al. 2006). This study thus provides evidence for the applicability of this approach in older stands and it also highlights the utility of incorporating a few basic ecophysiological principles into models of tree growth. In the case of aspen, results were less definitive. In previous work, the modeling approach worked well in young aspen stands (Seely and Welham 2010) but generated poor results in these older stands from one region (High Level) and was partly successful in another (Calling Lake). Although defoliation events have a significant impact on ring width in aspen (Hogg et al. 2002, 2005), across the three species the model was capable of simulating the relationship between climate and patterns of ring growth. The predictive capability of the model will be further improved within FORECAST Climate since the latter includes a representation of light and nutrient dynamics (as inputs to NPP)(see Kimmins et al. 2008). Including the impact of defoliation in models of forest productivity such as FORECAST Climate may also be required. One complication, however, is whether it is indeed possible to predict the frequency, severity, and duration of these events, particularly within the context of a changing climate.

3 DERIVING AND DOWNSCALING CLIMATE CHANGE PROJECTIONS

The first step in simulating climate change is to select one or more emission scenarios because projections of future climate from Global Circulation Models (GCMs) are derived, in part, in relation to a particular emissions scenario. There are about 40 scenarios identified by the Intergovernmental Panel on Climate Change, each making different assumptions of future greenhouse gas pollution, land-use and other driving forces such as technological and economic development. Most scenarios include an increase in consumption of fossil fuels though some project lower levels of consumption by 2100, as compared to 1990 levels. The emissions scenarios can be organized into one of six families, with each family comprised of scenarios that have common themes. In order of most pessimistic to the most optimistic, the six families are A1FI, A1B, A1T, A2, B1, and B2 (see Table 5). Barrow and Yu (2005) used these six scenario families in making climate change projections for Alberta, as follows.

Table 5. Summary descriptions of the six emission scenario families.

Emissions Scenario	Description
A1FI	A future world of very rapid economic growth and intensive use of fossil fuels
A1T	A future world of very rapid economic growth, and rapid introduction of new and more efficient technology
A1B	A future world of very rapid economic growth, and a mix of technological developments and fossil fuel use

Emissions Scenario	Description
A2	A future world of moderate economic growth, more heterogeneously distributed and with a higher population growth rate than in A1
B1	A convergent world with rapid change in economic structures, ‘dematerialisation’, introduction of clean technologies, and the lowest rate of population growth
B2	A world in which the emphasis is on local solutions to economic, social and environmental sustainability, intermediate levels of economic development and a lower population growth rate than A2

An Alberta Climate Model (ACM) has been developed that describes average provincial climate conditions for the 30-year period 1961 to 1990 for any geographic location in Alberta. The ACM was developed from Environment Canada’s raw monthly climate data for Alberta recording stations. It incorporates four primary climatic variables from which 13 climate-related variables were derived that were considered to be important in the distribution and responses of trees and other organisms to climate (Alberta Environment 2005).

Using the ACM as a baseline and a series of GCMs, Barrow and Yu (2005) simulated future climate scenarios for Alberta relative to the baseline period, projected for the 2020’s, 2050’s, and 2080’s. From a large suite of emission and GCM scenario combinations, five scenarios were selected based on predicted variation in temperature and precipitation during the summer season. Four represented the more extreme changes in mean temperature and precipitation, and one represented median conditions. These were: NCAR-PCM A1B (cooler, wetter), CGCM2 B2(3) (cooler, drier), HadCM3 A2(a) (warmer, wetter), CCSRNIES A1FI (warmer, drier) and HadCM3 B2(b) (median)(see Table 6).

Table 6. Attributes of the five scenarios selected by Barrow and Yu (2005) and used in this study.

GCM Acronym	Emissions scenario	Latitude resolution (°)	Longitude resolution (°)	Window limits
CGCM2	B2 (3)[2]	3.75	3.75	46.3886-64.9419°N 105-123.75°W
CCSRNIES	A1FI	5.625	5.625	41.5325-63.6786°N 106.875-123.75°W

GCM Acronym	Emissions scenario	Latitude resolution (°)	Longitude resolution (°)	Window limits
NCAR-PCM	A1B	2.8125	2.8125	46.0447-62.7874°N 106.875-123.75°W
HadCM3	A2 (a) [2]	2.5	3.75	45-65°N 105-123.75°W
HadCM3	B2 (b) [2]	2.5	3.75	45-65°N 105-123.75°W

[1] This reflects mean average temperature and precipitation during the summer season. This may not be the same as mean annual estimates for these variables (see, for example, Figure 14, and Barrow and Yu 2005).

[2] An ensemble experiment (see Barrow and Yu 2005) was carried out with this emission scenario and GCM. The number or letter is the experiment identifier.

The five climate change scenarios were downscaled by Golder Associates Ltd. for the northern Alberta region, and summarized as monthly modifiers of minimum and maximum temperatures and precipitation (see Barrow and Yu 2005, for an example of this procedure). The monthly modifiers were then used to modify daily values derived from historical weather records to simulate the daily values of future weather under different climate scenarios. Historical records from Fort McMurray weather stations during the 1961 to 1990 baseline period were used to create a century of climate change projections, beginning in 2011. Figure 13 shows the absolute changes (i.e., increases) in mean annual and growing-season (May through August) temperatures projected for Fort McMurray. Although there were considerable discrepancies among each scenario in terms of the overall rise in temperature, both the mean annual and growing-season temperatures were projected to increase through this century. This was not the case for precipitation (Figure 14). In 4 of the five scenarios, mean annual precipitation was projected to increase by as much as 23% in the latter part of this century (Figure 14A). Growing season precipitation, however, is projected to decline (Figure 14B). Overall then, temperatures will be warmer with wetter winters, drier summers, and longer growing seasons. The significance of these projected trends to regeneration and growth is discussed in Chapters 4 and 5, respectively.

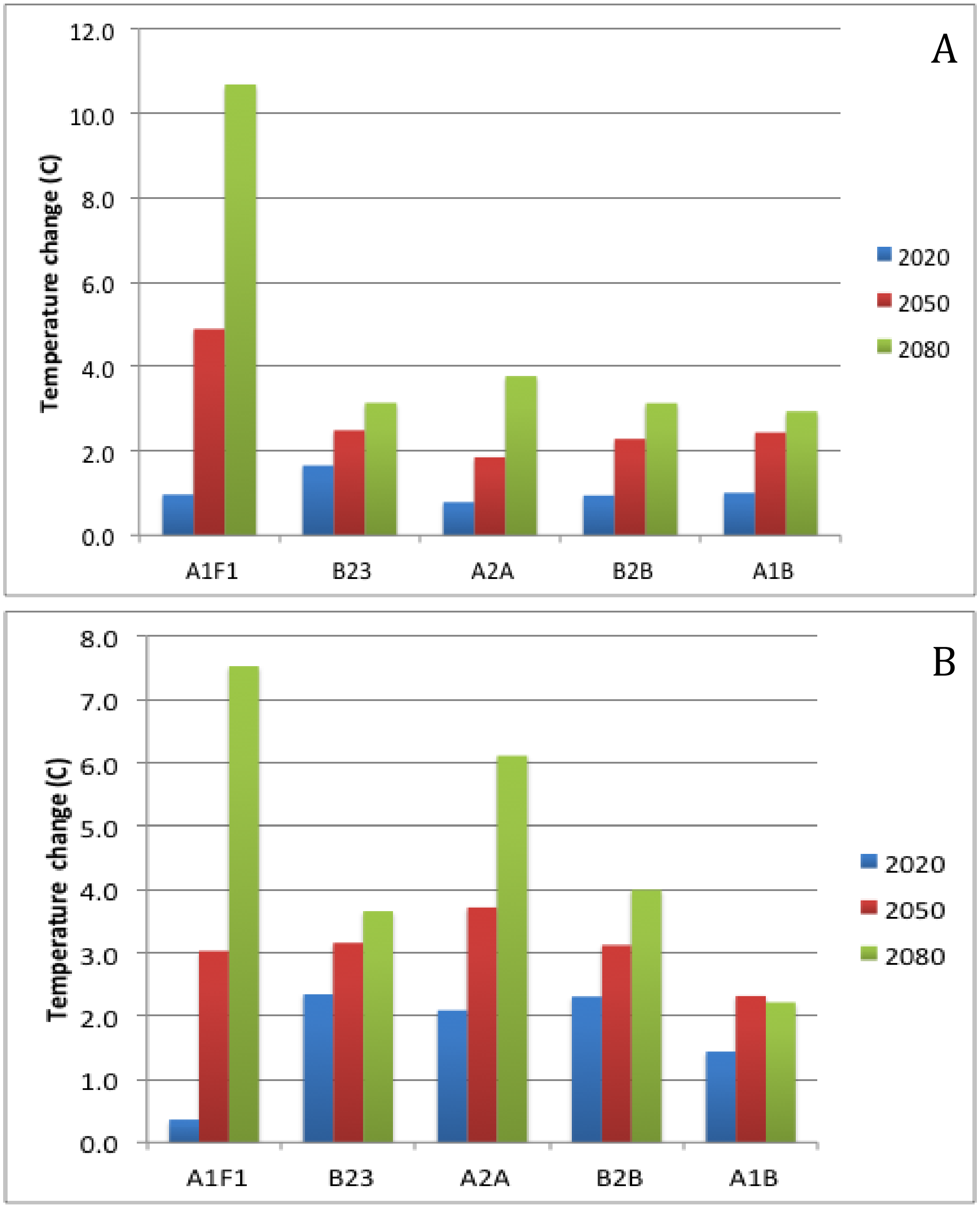

Figure 13. Absolute changes in mean annual temperature (A) and in the May–August period (B) in Fort McMurray, Alberta during three time periods (2020s, 2050s, and 2080s), as projected from five climate-change scenarios.
Note that temperature changes are relative to the 1961-1990 baseline period (see text for details).

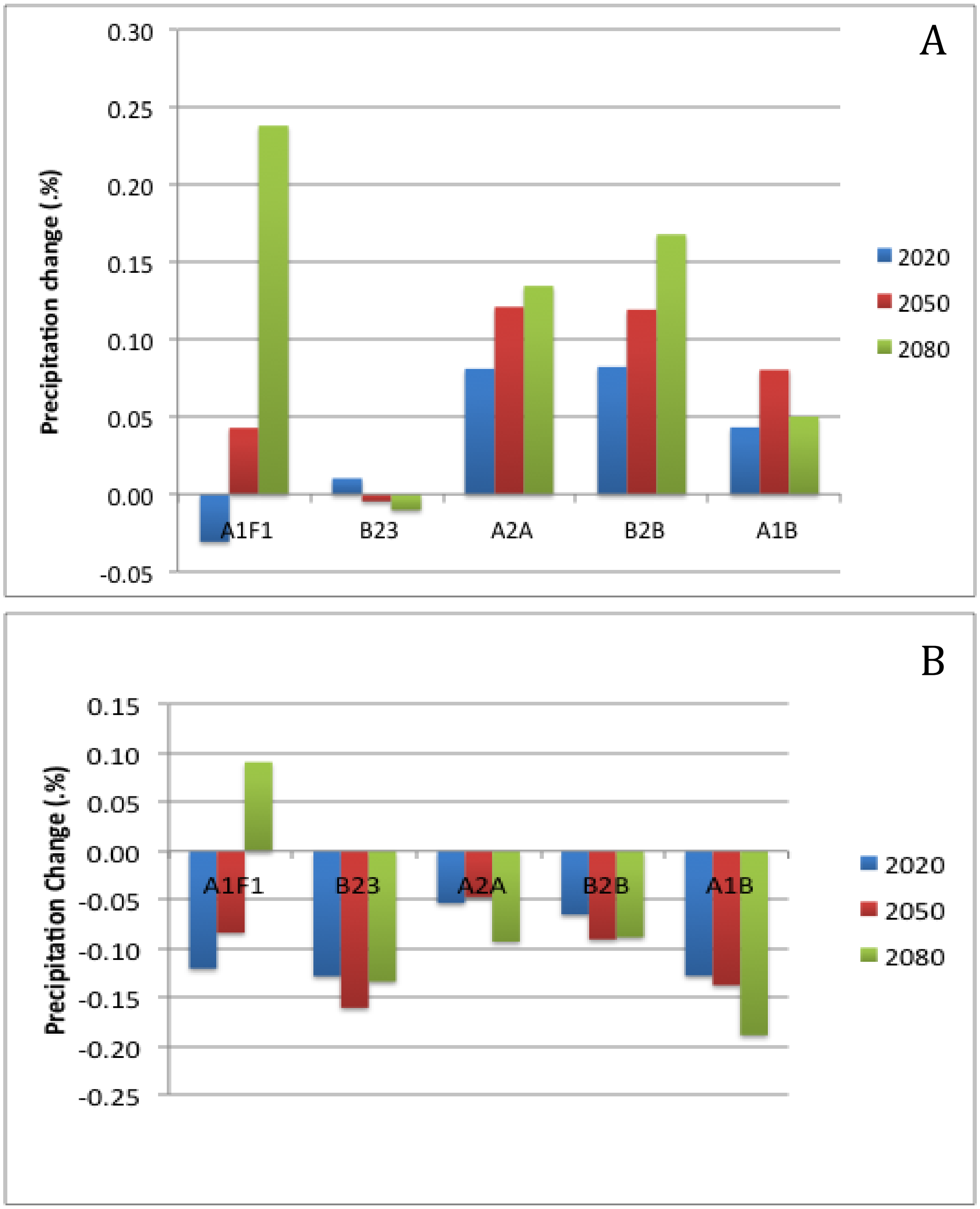

Figure 14. Proportional changes in mean annual precipitation (A) and in the May to August period (B) in Fort McMurray, Alberta during three time periods (2020s, 2050s, and 2080s), as projected from five climate-change scenarios.
Note that precipitation changes are relative to the 1961 to 1990 baseline period (see text for details).

4 PROJECTING ESTABLISHMENT SUCCESS UNDER CLIMATE CHANGE FOR SELECTED SITES IN BOREAL ALBERTA

Considerable effort has been spent in predicting the potential impact of climate change on species distributions. Much of this work, however, is based on correlational analyses of species presence and associated climate variables, with no explicit consideration of the underlying mechanisms or processes. One process critical to vegetation distribution is regeneration since species are most susceptible to climatic variation during the regeneration phase. Here, we use the Tree and Climate Assessment (TACA) model to assess the impact of climate change on the phenological and biophysical variables that control the regeneration phase of tree establishment. More specifically, TACA is used to assess the regeneration potential of three boreal tree species (white spruce *Picea glauca*, trembling aspen *Populus tremuloides* and jack pine *Pinus banksiana*) on different soil types in northern Alberta.

Model results indicate that under most scenarios, regeneration by all species is generally favoured by the warmer temperatures and higher annual precipitation predicted under climate change. One striking exception is the most severe emission scenario, where very warm conditions are a significant driver of moisture limitations and a low to non-existent regeneration potential. In the case of aspen, its ability to reproduce vegetatively improves the adaptive capacity of this species; clones can regenerate and persist by re-sprouting while maintaining their colonizing ability and potentially enhancing their distribution through seed-based regeneration.

As a model that incorporates many of the biophysical variables important to tree regeneration, TACA is a suitable tool for making realistic projections of the impact of climate and climate change on the regeneration potential of the boreal tree species in northern Alberta.

4.1 Introduction

At broad regional scales, plant species distributions are dictated largely by climate (McKenzie et al. 2003a, Woodward 1987). It is, however, the interaction of climate, biophysical variables, competition and disturbance that determine the mosaic of vegetation types within a given landscape. Changes in the climate regime are expected to alter this balance and the distribution of species along environmental gradients (Lo et al. 2010, Miller and Urban 1999). These range shifts could potentially result in development of novel species assemblages (Allen and Breshears 1998, Lo et al. 2010). Predicting how species distributions and community composition might be affected by a changing climate is thus of considerable importance. Selection of species deemed appropriate for planting prescriptions, for example, is based on what is locally common and/or of commercial importance. Current species distributions, however, are a reflection of historical climate regimes. If climatic conditions are substantially different going forward, the past may be a poor guide in planning for the future. Evidence in Alberta has indicated that in the most northerly populations, local trees may already be less adapted to climate change than transplants from elsewhere (Gray and Hamann 2011; Gray et al. 2011).

Common methods for predicting the impact of climate change on species include analysis of the tree line limit in northern and alpine environments (Dullinger et al. 2004), climate envelope modeling (Hamann and Wang 2006), or using dendroclimatology to link climate and tree ring growth (Wilmking et al. 2004). When combined with additional information such as soil types or topography, maps of potential habitat suitability under future climate regimes can be generated (e.g., Hamann and Wang 2006, Iverson et al. 2008). These approaches have their limitations, however (Pearson and Dawson 2003, Thuiller et al. 2008, Woodward and Beerling 1997), one of which is that they are simply correlational analyses with no explicit consideration of the mechanisms or processes that determine the presence or absence of a species.

One process critical to vegetation distribution is regeneration since species are most susceptible to climatic variation during the regeneration phase (Bell 1999, Grubb 1977). Regeneration refers to the renewal of a forest by natural, artificial, or vegetative means, and the ecological processes that affect seedling establishment, mortality, and growth to 1.3 m height (Canadian Forest Service 1995). Much of classical silviculture evolved as a means of solving regeneration problems, and the importance of forest regeneration in determining the composition and diversity of future forests is well recognized (Bergeron et al. 1998, Smith et al. 1997). Climate change is expected to have a significant impact upon boreal forest ecosystems (Chapin et al. 1992, Keyser et al. 2000), but the relationship between climatic factors and forest regeneration is poorly understood (Blanco et al. 2009). To incorporate climate change effects within the context of forest regeneration, information is required on the effect of thermal regimes on flower development and seed production, the potential colonization rates of individual species, the ecophysiology of seed production and seedling establishment, processes of seed dispersal, storage and germination, and the sensitivity to climate and elevated CO_2 of species that reproduce vegetatively (Price et al. 2001).

A variety of approaches have been used to explore the effects of climatic change on forest regeneration. Hogg and Schwarz (1997) combined a semi-quantitative regeneration index with a climatic moisture index developed for four vegetation zones in western Canada to predict conifer distribution. Cumming and Burton (1996) added aspects of species-specific phenology, and of local forest regimes to the patch model Zelig++ (Botkin et al. 1972, Urban 1993) to explore the possible consequences of four climate-change scenarios in eight distinct British Columbia forest regions. The model could thus account for differential species responses to changes in growing season length and seasonality (Cannell and Smith 1986) and to frost regimes. More recently, the TACA model was developed by further modifying ZELIG++ to assess the resistance and resilience of trees to climate change through changes in the breadth of a species' regeneration niche (Nitschke 2010, Nitschke and Innes 2008b; see below). It is able to identify the degree of change in phenological and biophysical variables that control tree establishment, growth and persistence. TACA has been used to predict the regeneration response of tree species to current and climate change scenarios in interior BC (Nitschke and Innes 2008a,b) and the Yukon (Nitschke 2009). Its development and application thus represents a significant improvement in the ability to predict the effect of a changing climate on tree species distributions.

In this report, the TACA model is used to assess the regeneration potential of three boreal tree species (white spruce *Picea glauca*, trembling aspen *Populus tremuloides* and jack pine *Pinus banksiana*) for different soil types in northern Alberta. TACA output is used to evaluate:
(a) how regeneration success of extant species may be affected by climate change; and

(b) whether a change in climate might favour the regeneration success of species not typically found on a given site. One possibility, for example, is that the xeric and sub-xeric sites typically occupied by jack pine may revert to grassland because they no longer possess the edaphic conditions sufficient to support a tree population. Alternatively, a regional drying trend may favour jack pine mixtures on sites now dominated by aspen and white spruce. These results have important implications for the planting prescriptions that constitute the basis of reclamation activities (see, for example, Alberta Environment 2010). Finally, the regeneration probabilities associated with particular tree species as derived from TACA will also be used as input to FORECAST Climate model simulations.

4.2 Materials and Methods

4.2.1 *The TACA Model*

TACA analysis output provides the response of trees in their regeneration niche to climate-driven phenological and biophysical variables (Figure 15; see Nitschke 2010 and Nitschke et al. 2008a,b for further details). TACA is therefore a vulnerability analysis tool that uses the following driving variables to determine the probability of species presence/absence:

- Growing degree-day thresholds;
- Species-specific threshold temperature;
- Minimum metabolic temperature;
- Chilling requirement;
- Bud break degree day threshold;
- Drought tolerance;
- Frost tolerance.

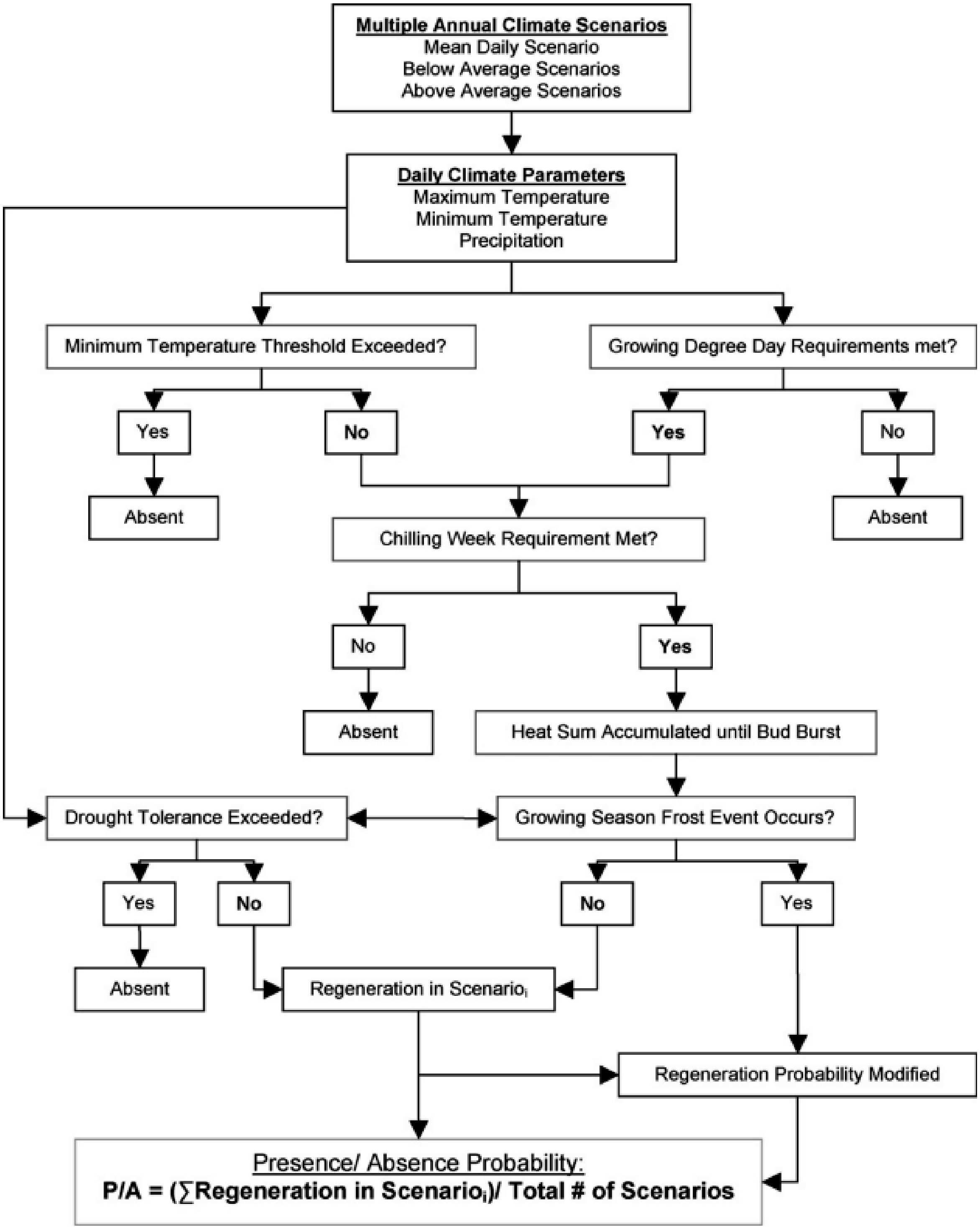

Figure 15. Diagram of model components and information flow in TACA (Nitschke 2010).

Minimum and maximum growing degree-day (GDD) thresholds are used to determine the lower and upper relationship between temperature and growth (Urban 1993). GDD are calculated by summing the number of degree-days above a species-specific baseline temperature for an entire year. If the GDD minimum threshold is not met or the maximum threshold is exceeded, it is assumed that the regeneration niche of a species has not been met, resulting in mortality (He et al. 1999) or preventing a species from becoming established (Dale et al. 2001, Franklin et al. 1992). It should be noted that the regeneration niche of a species is narrower than the realized niche of a mature tree and so this assumption does not necessarily preclude the presence of mature trees (McKenzie et al. 2003b). Species-specific baseline temperatures are used to initiate physiological activity (Fuchigama et al. 1982). The accumulation of GDD occurs until a species-specific heat sum is reached, which then initiates bud break (Fuchigama et al. 1982). The timing of bud break is expected to occur at earlier dates due to climatic change, which may increase the risk of mortality by early spring frosts (Cannell and Smith 1986; Lavender 1989).

The probability of presence/absence is determined based on the average probability of a species meeting all phenological and biophysical criteria (see Figure 15) for a given climate scenario. A single climatic scenario represents one year of weather. Multiple climate scenarios are run in TACA and are used to determine a species presence/absence probability under historic, current and/or future climatic scenarios. Future scenarios can be based on predictions from global circulation models or user-defined. A species must meet the GDD, chilling requirement, minimum temperature and drought parameters in a given scenario. If this is the case, its regeneration success is then potentially modified by the probability of frost damage. Frost damage is a product of the probability of frost events occurring multiplied by the frost modifier for a species (see Nitschke 2008a,b, for examples). A species meeting all criteria receives a presence score of one and the climate conditions are assumed to be in the optimal range of the species' regeneration niche. A score of zero means that that species never satisfied the required parameters, and climate conditions were thus outside the regeneration niche. Probabilities between one and zero are a result of the suite of parameters being met in a proportion of the scenarios in combination with the probability of frost damage.

4.2.2 *Model Calibration*

4.2.2.1 Deriving the Climate Scenarios

TACA uses daily climate data nested within an annual time step. Its key parameters are maximum temperature, minimum temperature and precipitation. Historical climatic data series were obtained for Fort McMurray (56° 39' N, 111° 13' W, 369.1 m.a.s.l., average annual temperature 0.7 °C, average annual precipitation 455.5 mm) from Environment Canada's National Climate Archive, (http://www.climate.weatheroffice.ec.gc.ca). Historical climate records were used to create scenarios derived from 10 years of climate data and designed to represent the variability in the climate record, as follows. First, mean annual temperature (MAT), total annual precipitation (TAP) and an annual heat moisture index (AHMI; see Nitschke 2010 for details), were determined for each year in the climate record.

The AHMI is calculated as:

$$\text{AHMI} = (\text{Mean Annual Temperature}+10) / (\text{Annual Precipitation}/1000)$$

Each year was then ranked independently according to each of the three variables. Five years from each of mean annual temperature and annual precipitation were selected that represented the 90%, 75%, 50%, 25% and 10% percentiles of their distributions. If the same year occurred for each variable at the same percentile, the corresponding percentile for AHMI value was used to select the unique year for each of MAT and TAP. The selected years from the Fort McMurray historical weather records are shown in Table 7. These years represent 10 observed climate scenarios.

Table 7. Representative years selected from historical weather records at Fort McMurray as classified by annual average temperature or annual accumulated precipitation (see text for details).

Percentile	**Temperature**	**Precipitation**
95%	2006	1996
75%	1997	1988
50%	1985	2008
25%	1961	1953
10%	1966	2004

To simulate the effect of a changing climate, five climate change models, each with different scenarios of future CO_2 trends, were selected (Table 8), and are identical to those used by Barrow and Yu (2005) in their assessments for Alberta. It is important to note that no single climate change model or its associated emissions scenario can be deemed ‘correct’ (Barrow and Yu 2005). In this regard, each model’s projections should be considered as equiprobable and including a suite of models is thus an important step in deriving a sense of the variability in output and in gaining an understanding of its impact on germination success. All of the climate change scenarios had been downscaled by Golder and Associates Ltd. (Calgary, Alberta) for the northern Alberta region and were supplied to the project by Alberta Environment. Data were provided as summarized in monthly modifiers of minimum and maximum temperatures and precipitation that reflect each of the climate change scenarios (see Appendix). The monthly modifiers were used to adjust the daily values derived from the historical weather records of the selected years (see Table 7) to simulate the daily values under a future climate. These daily data are then used as input to the TACA model.

Table 8. Climate models and scenarios selected to simulate climate change in 2020, 2050 and 2080.
See Appendix for values of monthly modifiers for minimum temperature, maximum temperature and precipitation.

Model	**Scenario**	**Description**	**General attribute**[1]
CCSRNIES	A1 F1	Rapid economic growth, intensive fossil fuel use	Warmer, drier
CGCM2	B2(3)	Intermediate economic development, lower population than in A2	Cooler, drier
HADCM3	A2(a)	Moderate economic growth, higher population than in A1	Warmer, wetter
HADCM3	B2(b)	Intermediate economic development, lower population than in A2	Median
NCARPCM	A1 B	Rapid economic growth, less intensive fossil fuel use	Cooler, wetter

[1] For the 2050s, and compared to the median (HADCM3 B2(b)). Note that all models project an overall increase in mean annual temperature (see Appendix).

4.2.2.2 Tree Species Parameters

The species-specific parameters for white spruce, trembling aspen, and jack pine used to calibrate TACA are described in Table 9. All parameters are based on empirical relationships and incorporate ecological and silvical characteristics as described in Klinka et al. (2000).

Table 9. Parameters used to calibrate TACA for three tree species[1].

Parameter	**Trembling Aspen**		**White Spruce**	**Jack Pine**
	Seeds	VR[2]		
Physiological Base Temperature (°C)	3.5	3.5	2.7	2.8
Heat Sum for Bud Burst (GDD)	189	189	147	108
Chilling Requirement (Days)	70	60	42	56
Minimum Temperature (°C)	-80	-80	-70	-85
Drought Tolerance	0.40	0.40	0.34	0.42

Parameter	**Trembling Aspen**		**White Spruce**	**Jack Pine**
	Seeds	VR[2]		
GDD Minimum	226.8	227.0	129.6	250.0
GDD Maximum	4414	4414	3459	4500
Frost Tolerance	0.90	0.95	0.90	0.90
Frost Season	300	320	305	315
Wet Soils	0.30	0.30	0.50	0.25
Soil Temperature (°C)	5	5	5	8
Heat Sum (GDD)	80	80	129	120
Stratification (days)	0	0	0	28
Chilling Heat Sum Factor	1	1	1	0.75
Germination Moisture Threshold	-0.80	-0.90	-0.50	-0.90
Min Temperature for Germination	3.5	3.5	2.7	2.8
Max Temperature for Germination	32	32	35	30
Vegetative Reproduction	0	1	0	0
Low Nitrogen Availability	0.30	0.30	0.30	0.85
Medium Nitrogen Availability	1	1	1	1
High Nitrogen Availability	0.75	0.75	0.75	0.20

[1] As derived from Asselin et al. (2003), Bonan (1989, 1990), Burton and Cumming (1995), Cumming and Burton (1996), Despland and Houle (1997), Durzan and Chalupa (1968), McKenzie et al. (2003a,b), Nitschke and Innes (2008 b), Urban et al. (1993) and Zolbrod and Peterson (1999). See Nitschke and Innes (2008 b) for a further description of these variables.

[2] Vegetative reproduction.

The two sets of values used to simulate trembling aspen (Table 9) constitute regeneration from seeds or from a combination of seeds and vegetative reproduction (VR). Seedlings are exposed to a smaller soil profile since they depend only on their developing root system, while root suckers gain access to a larger portion of the rooting zone because they are derived from existing root biomass. In addition, root suckers are more tolerant of frost and drought stress compared to seed germinants.

4.2.2.3 Soil Parameters

Three soil types were represented in the TACA simulations representing the same three sites used to calibrate ForWaDy (see Chapter 3) and the FORECAST Climate submodel of tree-ring growth (Chapter 5). In addition, TACA requires data that define the characteristics of the germination layer. All data used in calibrating the soil parameters are listed in Table 10.

In general, Fort Chipewyan had higher inherent productivity than either Calling Lake or High Level. This included a deeper rooting zone, greater moisture storage potential, and higher nitrogen availability (Table 10). Calling Lake, in turn, had better moisture storage potential than High Level though both sites are low levels of nitrogen availability.

Table 10. Soil parameters in TACA describing three soil types in northern Alberta, plus the germination seedbed[1].

Soil Parameters	**Fort Chipewyan**	**Calling Lake**	**High Level**	**Germination**
Soil Moisture Regime	Sub Mesic	Sub Mesic	Sub Mesic	Mineral
Soil Texture	Loam / Silt Loam	Loamy Sand	Loam / Silt Loam	Loamy Sand
Soil Rooting Zone Depth (m)	0.90	0.60	0.50	0.10
Coarse Fragment (%)	40	25	30	25
Water Holding Capacity (mm/m of soil)	362	362	290	192
AWHC[2] (mm)	195.5	162.9	101.5	14.0
Field Capacity (mm/m of soil)	453	453	373	247
Available Field Capacity (mm)	244.6	203.9	130.6	18.5
Percolation (mm/day)	15	16	13	-
Nitrogen Availability	Medium	Poor	Poor	Poor

[1] Data derived from Alberta Environment (2006), Bock et al. (2006), Pedocan Land Evaluation Ltd. (1993) and Tajek et al. (1989).

[2] Available water holding capacity.

4.3 Results and Discussion

4.3.1 *Jack Pine*

Projected regeneration probabilities for jack pine in northern Alberta under five different climate change scenarios are presented in Figure 16. A moderate increase in regeneration by 2050 was projected for all future climate scenarios (generally between 15% and 30%) for the three soil types (Figure 16). Thereafter, the regeneration probability typically increased for all climate scenarios, with the exception of the A1F1 scenario (Figure 16). In the latter case, regeneration was projected to decline significantly in the 2080's to levels that were below values based on current climate conditions.

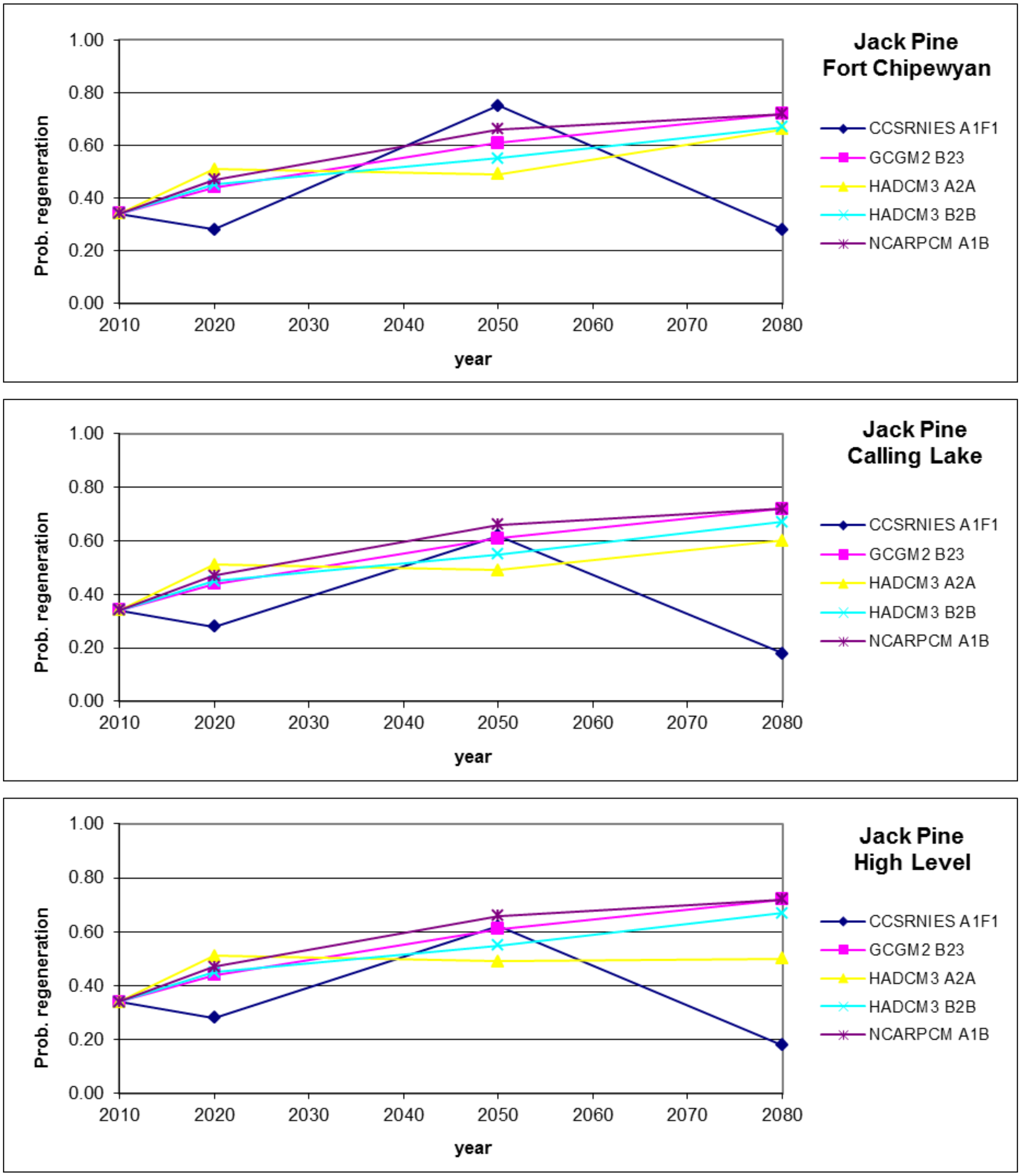

Figure 16. Probability of jack pine regeneration in northern Alberta at three sites constituting different soil types for five future climate change scenarios.

The A1F1 scenario is the most pessimistic in terms of projected emissions (at least among those considered here) because of its assumptions of rapid economic growth and intensive fossil fuel use. Consequently, under this scenario the CCSRNIES model predicted an increase in mean annual temperature by 2080 of about 10.8 °C, roughly twice the projections made under of the other emissions scenarios (see Figure 14A).

The northern limit of jack pine is determined by the short growing season and the low GDD (McLeod and MacDonald 1997). The warming trends predicted under the emissions scenarios (see Chapter 3) should therefore have a beneficial effect on a number of biophysical variables (Table 3) and the associated regeneration success, as predicted by the TACA model. Any increase in temperature will have a positive impact on the species, however, only if its physiological and ecological tolerance limits are not exceeded (Matyas 1994). This may be the case under the A1F1 emissions scenario, which is predicted to result in conditions warmer and drier than the median (see Table 6). The annual AET/PET ratio (used in TACA as an index of aridity) for this climate scenario declined from an average of 0.872 in 2020 to 0.628 by 2080 (data not shown), indicating that conditions were indeed becoming increasingly moisture-limited (Hidalgo et al. 2006). Hence, any benefit to regeneration from the increase in the length of the growing season during the short and medium term (i.e., up to the 2050s) will be more than offset by moisture deficits incurred in the latter half of this century, if this scenario is indeed an accurate representation of the future emissions profile (and the CCSRNIES model provides a reasonable representation of the future climate). Under current climatic conditions, moisture deficits are significant at the southern edge of this species' range in Alberta where soil moisture is a major limiting factor (Ritchie 1987).

One important feature of jack pine reproductive ecology is its production of serotinous and semi-serotinous cones. In this respect, the species relies on fire to provide the conditions necessary for cones to open and release seed (McLeod and Macdonald 1997). Serotiny is not represented in TACA. This is likely not problematic for projections of the regeneration probability, however, since increases in temperature will be positively correlated with fire frequency. Hence, wildfires are not likely to be the factor that most constrains regeneration potential. It has been projected, for example, that the area burned in Alberta by wildfires could increase up to 29% during this century if CO_2 concentrations rise to a level three-fold higher than in pre-industrial times (Tymstra et al. 2007).

4.3.2 ***White Spruce***

Rweyongeza et al. (2007) found that annual moisture index (AMI), expressed as a ratio of GDD above 5°C and mean annual precipitation, was the major determinant of survival and growth of white spruce in Alberta. In this respect, the southern limit of white spruce in central and western Canada appears to be defined by available moisture (Chhin et al. 2004, Chhin and Wang 2008, Hogg 1994), whereas the northern tree line is limited by growing season temperatures (Payette, 2007).

Projected regeneration probabilities for white spruce in northern Alberta under the five climate change scenarios are presented in Figure 17. Overall, regeneration probabilities varied by less than 15% of the starting values in four of the 5 climate change scenarios. This contrasts with jack pine, which showed substantial improvements in regeneration potential associated with warming temperatures, particularly when this was accompanied by wetter than median conditions. As was also the case with jack pine, a striking exception was the CCDRNIES A1F1 scenario. In Fort Chipewyan and Calling Lake, regeneration probabilities were relatively constant through 2050 under this scenario but then declined significantly thereafter (Figure 17). In the case of High Level, there was a decline in 2050 and further drop in 2080. As noted above, the A1F1 scenario is the most pessimistic of the projected emissions scenarios. It thus appears that under this scenario, white spruce may have difficulty successfully regenerating in northern Alberta late in this century.

Under the moderate to low emissions scenarios (A2 and B2; Table 2), white spruce regeneration may be slightly favoured over the long-term because temperature and moisture regimes are predicted to ameliorate (see Table 8, for example). These results are in contrast to Rweyongeza et al. (2007). They used a future climate scenario very similar to the HadCM3 scenario described in Barrow and Yu (2005; see Table 8), applied over the years 2030 to 2039 and which corresponded to a moderate change in temperature and precipitation. Under the resulting predictions of AMI, survival and growth of white spruce would decline substantially in those parts of northern and central Alberta where drought already exists. However, during the same period, survival and growth would increase substantially in the foothills and Rocky Mountain region where growth is currently limited by low GDD in these high elevation sites.

4.3.3 ***Trembling Aspen***

Projected regeneration for aspen in northern Alberta under the five climate scenarios is presented in Figure 18. Trembling aspen shows a more variable response than the conifers among the climate models and these trends were consistent between the three sites. Regeneration success was higher for vegetative reproduction than from seed for any given climate scenario and all periods (Figure 18). This is not unexpected since new clonal growth is aided by its physiological attachment to the parent ramet (Table 9 exemplifies some of these differences). In the case of seed, regeneration potential is projected to generally increase from 17% to 33% by 2050 and remain constant thereafter. One exception is the HADCM3 A2(a) scenario where a decrease in regeneration potential is projected to occur by 2050 and stabilization at around a 14% regeneration probability by 2080. Under CCSRNIES A1F1, an increase in regeneration potential is predicted by mid-century. However, thereafter regeneration by seed is highly improbable suggesting that vegetative reproduction is the only viable option for regeneration under this (most pessimistic) emissions scenario (see Figure 18).

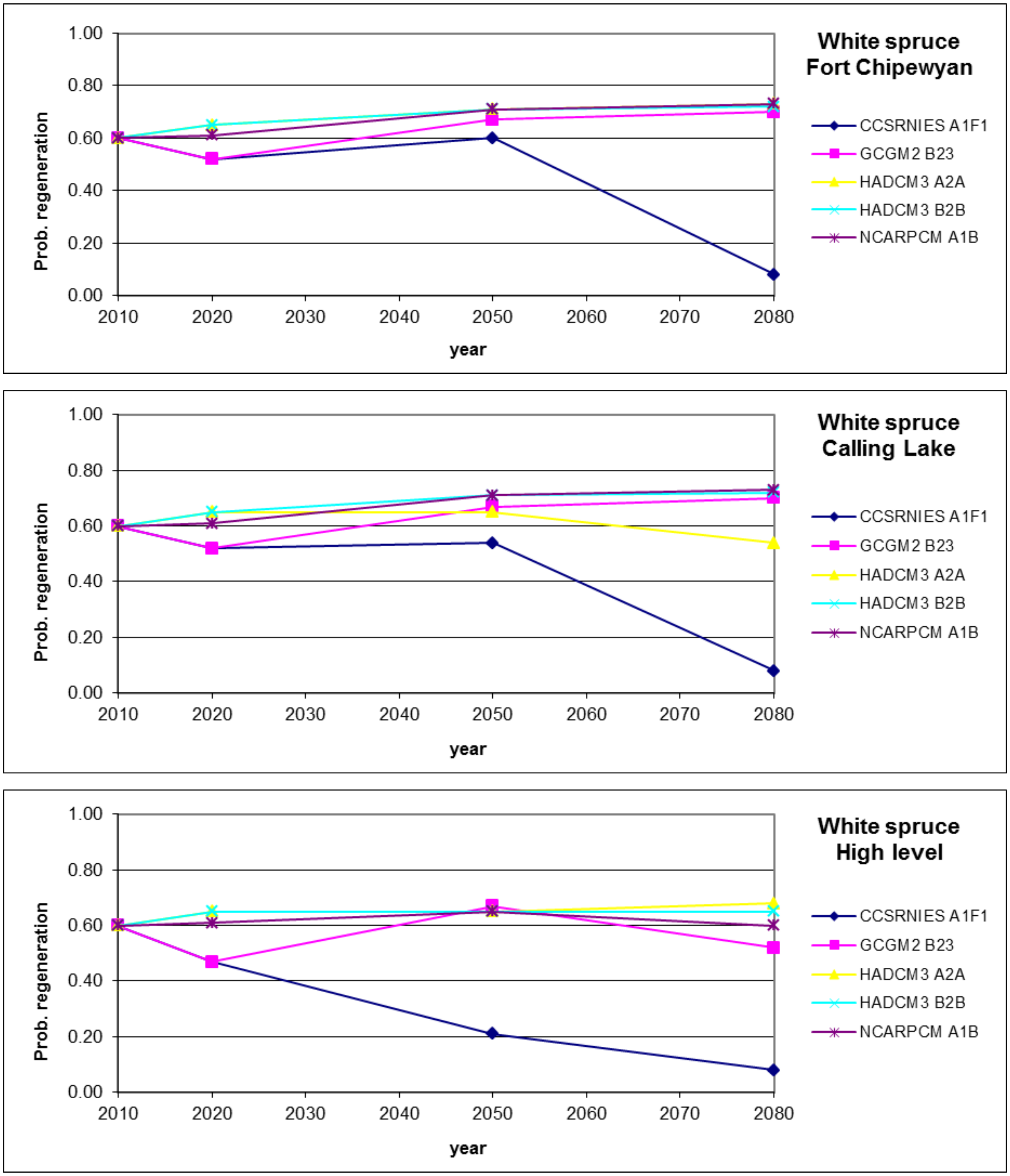

Figure 17. Probability of white spruce regeneration in northern Alberta at three sites constituting different soil types for five future climate change scenarios.

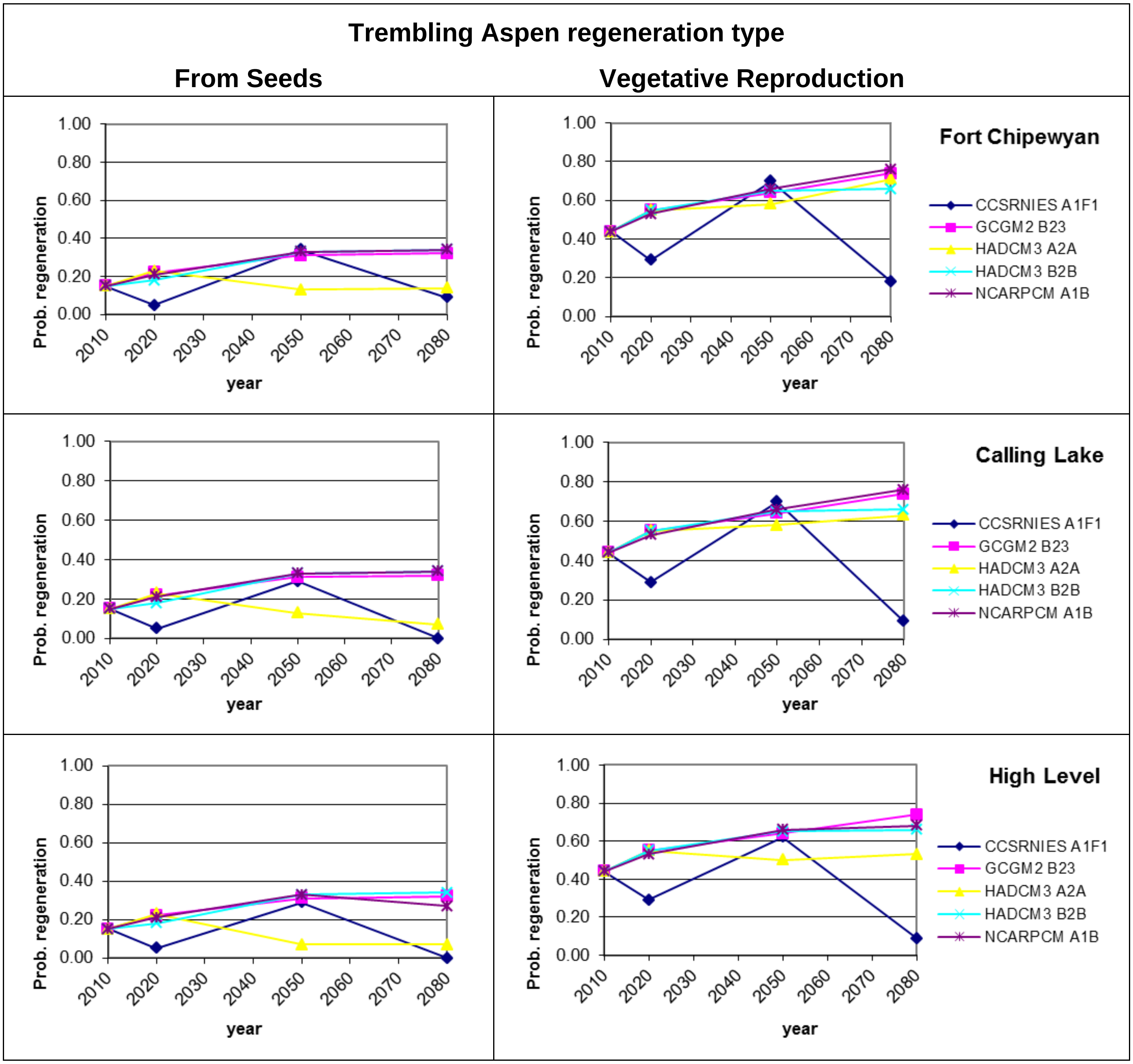

Figure 18. Probability of aspen regeneration in northern Alberta from seeds (left panels) and vegetatively (right panels) at three sites constituting different soil types for five future climate change scenarios.

Trembling aspen is the most widely distributed tree in North America (Perala 1990) with a broad ecological amplitude, occupying sites that vary from moderately dry to very moist, and poor to very rich (Klinka et al. 2000). Regeneration from seed can be moisture-limited, which could result in slow and patchy regeneration (Hogg and Wein 2005). Aspen is also sensitive to low soil temperature, and growth and vegetative reproduction increase with soil temperature (Peng and Dang 2003, Peterson and Peterson 1992). The increase in regeneration success over moderate changes in climate (the B2(b) and B2(3) scenarios, for example; see Table 8) is thus consistent with the autecology of this species.

The fact that aspen can utilize both seed and vegetative reproduction has important implications for maintaining its distribution in a changing climate regime. Seed germination and survival rates are typically very low (see Figure 18) but tend to be highest on severely burned surfaces with exposed mineral soil (Johnstone and Chapin 2006). Under warmer, drier conditions (see Table 8) fire frequency and intensity are likely to increase thereby promoting conditions suitable for germination. Seedling survival, however, will depend on the appropriate timing and amounts of precipitation. In this respect, Elliot and Baker (2004) reported good seed regeneration in quaking aspen during cool and moist periods and a reliance on re-sprouting when conditions were predominantly warm and dry. This phenomenon highlights an adaptive capacity in this species whereby clones are able to persist after disturbance by re-sprouting while maintaining their colonizing ability and potentially enhancing their distribution through seed-based regeneration (Hogg and Wein 2005).

How important is regeneration success to maintaining the presence of aspen in northern Alberta? For the most part, aspen forests in Alberta are moisture limited (Hogg et al. 2008) and thus are vulnerable to warming and drying trends that are typical of most of the climate change scenarios for the province (see for example, Barrow and Yu 2005). The aspen parkland region in particular represents the southern ecotone of the boreal forest, and is an area where aspen may be the most vulnerable (Hogg and Hurdle 1995, Hogg and Wein 2005). In northern Alberta, Calef et al. (2005) suggested that deciduous forest would see an expansion in distribution if fire intervals were reduced along with warming and/or increased precipitation. Similarly, Leonelli et al. (2008) predicted that aspen will be negatively affected by climate change on sites where moisture and nutrient resources are limiting, but should maintain growth or increase productivity on favorable sites. Nevertheless, a severe warm, dry trend as predicted under the CCSRNIES A1F1 scenario impairs regeneration (Figure 18) and is likely to also cause dieback in mature stands, an effect already reported in the central boreal region (Frey et al. 2004).

As a model that incorporates many of the biophysical variables important to tree regeneration, TACA appears to be a suitable tool for making realistic projections of the impact of climate and climate change on the regeneration potential of the boreal tree species in northern Alberta. Overall, regeneration potential improved as temperatures ameliorated with climate change though this was not the case under the most extreme emissions scenario (A1F1).

5 EVALUATING FUTURE ECOSYSTEM DEVELOPMENT IN OIL SANDS RECLAMATION WITH THE FORECAST CLIMATE MODEL

The focus of this chapter is to evaluate future ecosystem development in jack pine, aspen and white spruce with the FORECAST Climate model after incorporating the five climate change scenarios developed in Chapter 3.

Stands initiated under current climatic conditions (in year 2011) are predicted to experience enhanced long-term productivity (to year 2111) under a changing climate regime, as compared with the growth that would have occurred if historical climatic conditions been maintained over the next 100 years. Although there was a substantial range among GCM scenarios in their projections of stemwood growth, the minimum projection was always greater than that derived from the historical climate data. In general, forest productivity in northern latitudes is temperature-limited. Model output suggests that tree productivity in the region may be enhanced through much of the 21st century as a result of improvement in the thermal regime (longer growing seasons, warmer soil, increased decomposition) and potentially an overall increase in available moisture, that more than compensates for any negative impact associated with growing season moisture limitations. In general, understory plant communities were negatively affected by the projected increase in overstory productivity under climate change.

Model projections indicated that habitat suitability under climate change would be improved overall, relative to values derived using the historical climate regime. The greatest improvement in the HSIs was for the d1 (aspen) ecosite and the least in the d3 (white spruce) ecosite.

Taken together, the model results suggest a number of management responses within the context of oil sands reclamation that can reduce risk, and help mitigate carbon emissions and retain habitat features, at least for some species. These are:

1. **Minimize the forest cover removed as part of mine operations.** Retention of forest cover improves the carbon balance and, depending on its areal extent and spatial configuration, can also serve as refugia for wildlife on the mine footprint.
2. **Return forest cover as soon as is practicable.** Forest productivity under climate change is enhanced, which will translate into higher carbon sequestration and improved habitat suitability as compared to the reference case (the historical climate regime). Returning forest cover quickly thus serves to leverage the benefits from improved productivity.
3. **Expand forest carbon sinks to promote carbon storage and development of habitat attributes.** Adding fertilizer annually for 5 to 10 years after planting, particularly on poor sites, will promote both tree and understory productivity, and thus carbon storage and development of habitat attributes. Retaining and adding slash and other dead organic matter after land clearing will also increase carbon stores (at least temporarily) but more importantly create valuable habitat.
4. **Encourage species mixtures over monoculture plantations.** Conifer monocultures and extensive tracts of aspen-dominated forests are vulnerable to outbreaks of insect defoliation and bark beetles. Planting tree species in mixtures or at the very least, reducing the areal extent of monocultures may help mitigate risk, enhance forest resilience, and/or prevent large-scale pathogen outbreaks.
5. **Increase protection measures.** Mine operators should develop and implement regular monitoring programs on their reclaimed areas to identify potential threats to stand health before they become unmanageable.

6. **Enhance fire suppression capability.** An increased risk of forest fires (both in frequency and severity) is predicted to occur with climate change. This could result in significantly greater releases of carbon as material is consumed, but can also generate rapid and pronounced shifts in community composition.

5.1 Introduction

Changes in the climate regime could have a significant impact on forest ecosystem development (growth, tree species composition, and ecosystem productivity), the goods and services they provide, and the wildlife species that depend on them. The standard approach to projecting stand development has largely relied upon the use of models calibrated from historical observations of tree growth. The core assumption underlying this approach is that past production is a reasonable predictor of future production because conditions for growth will remain essentially unchanged. If projected changes in climate are indeed realized, however, the suitability of these relatively simple empirical models is highly questionable. This point is well illustrated by the work of Hogg et al. (2005); their study of climatic variation and insect defoliation demonstrated how quickly a change in growing conditions can influence aspen growth and yield.

One alternative is to develop models that predict a climate-growth response from parameters fitted using empirical data of climate in conjunction with associated changes in growth (see for example, Girardin et al. 2008). While this type of empirical modelling approach captures the statistical relationship between growth and climate, it provides no understanding of biological mechanisms and its predictive capacity is limited to the data range from which it was calibrated (see Girardin et al. 2008, for a more complete discussion). Process-based growth models, on the other hand, use physiological and physical principles in conjunction with simulated edaphic conditions to project forest development and productivity. ‘Pure’ process models tend to be more complex than their empirical counterparts (see Dixon et al. 1990, for examples), which often makes their calibration difficult and inhibits portability. A practical compromise is the hybrid simulation (HS) approach (see Kimmins et al. 2010). In an HS model, empirical data are used by the model to ‘self-calibrate’ at least some of its ecosystem processes. This has the benefit of reducing the calibration load while ensuring simulated processes are linked directly to empirical measures (see below for a description of the FORECAST Climate HS model). Regardless of the type of process model, their basic structure means that forest productivity is embedded within an environment that includes the simulation of climatic conditions. It is therefore possible to project the impacts of future climate scenarios on forest ecosystem development. Integrating climate-sensitive output into the decision support tool will improve its capacity to evaluate the relative risk associated with alternative management practices.

The focus of this chapter is to evaluate future ecosystem development within the context of oil sands reclamation using the FORECAST Climate model after incorporating the climate change scenarios developed in Chapter 3. One possibility is that longer, warmer summers result in lower tree growth and productivity if they are accompanied by prolonged periods of water stress (Fritts 1976, Kozlowski and Pallardy 1997b). Hogg et al. (2005) examined factors affecting growth of western Canadian aspen forests during a fifty-year period. Most of the variation in growth was explained by inter-annual variation in a climate moisture index in combination with insect defoliation. Recent evidence indicates a widespread increase in tree mortality rates through the western US, with regional warming and consequent increases in water deficits as likely contributors (van Mantgem et al. 2009). Alternatively, warmer temperatures could increase the frost-free period, particularly in northern latitudes, leading to longer growing seasons and increased productivity (MacDonald et al. 1998). Many studies have found a positive response between summer temperatures and/or annual temperatures and the radial growth of *Picea glauca* (white spruce) in northern Canada and Alaska (see Schweingruber et al. 1993, Szeicz and MacDonald 1995, and references therein). In addition, white and black spruce recruitment has been positively correlated with increases in summer temperatures (MacDonald et al 1998).

5.2 Materials and Methods

5.2.1 *FORECAST Climate*

5.2.1.1 The Tree Growth Submodel

FORECAST Climate is an extension of the FORECAST model (Kimmins et al. 1999), a management-oriented, stand-level forest growth simulator. FORECAST has been under development and application for more than four decades and its output has been evaluated against field data for growth, yield, ecophysiological and soil variables (Bi et al. 2007, Blanco et al. 2007, Seely et al. 2008). Recently, the model and its output were subject to a successful independent audit to confirm its suitability as a tool for simulating the carbon balance in forest ecosystems.

FORECAST employs a hybrid approach whereby local growth and yield data are used to derive estimates of the rates of key ecosystem processes related to the productivity and resource requirements of selected species. This information is combined with data describing rates of decomposition, nutrient cycling, light competition, and other ecosystem properties to simulate forest growth under changing management conditions (Figure 19).

Decomposition and dead organic matter dynamics are simulated using a method in which specific biomass components are transferred, at the time of litterfall, to one of a series of independent litter types. Decomposition rates used for the main litter types represented in the model are based on the results of extensive field incubation experiments (Prescott et al. 2000, Trofymow et al. 2002). Residual litter mass and associated nutrient content is transferred to active and passive humus pools at the end of the litter decomposition period (when mass remaining is approximately 15% to 20% of original litter mass). Mean residence times for active and passive humus types are typically in the range of 50 and 600 years, respectively. Modifications to the various processes represented within FORECAST due to the influence of climate are described below.

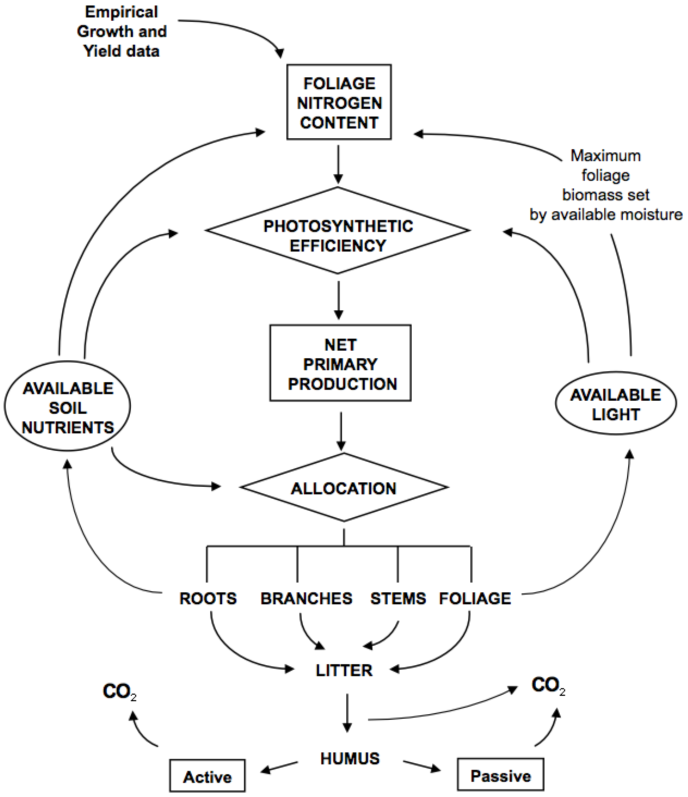

Figure 19. A schematic illustration of the key ecosystem processes and flows represented in FORECAST.

5.2.1.2 ForWaDy: The Forest Hydrology Submodel used in FORECAST Climate

In Chapter 2, the forest hydrology model, ForWaDy, was described and used to integrate climate variables (moisture and temperature) with annual net primary productivity, in order to calibrate a sapwood growth model, the latter of which is an important component of FORECAST Climate. The analysis included the relative impact of soil cover depth, minor vegetation competition, and the historical climate record, on the development of tree water stress (calculated by ForWaDy as a transpirational deficit index; see Chapter 2 for details). Although ForWaDy was used as a stand-alone model in Chapter 2, the model is also fully integrated within FORECAST Climate. The calibration data used in its application within FORECAST Climate are listed in Tables 11 and 12.

Table 11. Parameter values used in ForWaDy that are specific to simulating evapotranspiration.

SPECIES	**Maximum LAI**[1]			**Canopy**		**Permanent Wilting Point** (%)				**Max. Root Depth**
	Submesic	Mesic	Subhygric	Albedo	Resistance[2]	Humus	Submesic	Mesic	Subhygric	(cm)
Aspen	2.0	3.0	3.5	0.12	0.15	0.13	0.10	0.17	0.30	100
White spruce	4.0	4.25	4.5	0.12	0.15	0.15	0.11	0.18	0.32	75
Jack pine	2.5	3.0	3.5	0.12	0.30	0.08	0.07	0.12	0.21	110
Calamagrostis canadensis[3]	-	-	-	0.14	0.25	0.10	0.10	0.13	0.23	75
Mid-ser Forb	-	-	-	0.12	0.20	0.10	0.10	0.13	0.23	75
Hazelnut	-	-	-	0.12	0.13	0.15	0.14	0.18	0.32	75
Green Alder	-	-	-	0.12	0.15	0.13	0.13	0.17	0.30	75

[1] The representation of understory foliage biomass is simpler than for trees. Data on LAI is not needed. For trees, LAI is different for each site quality simulated.

[2] "Canopy resistance" refers to the stomatic resistance to lose water from the leaves.

[3] A grass species.

Table 12. Parameter values used in ForWaDy that are specific to simulating soil water availability by ecosite.

Ecosite	**Edaphic conditions**	**Soil Texture class**	**Coarse Fragment %**	**Mineral soil depth (cm)**	**Initial Snow pack (mm)**
a	subxeric poor	Loamy sand	45	45	60
b	submesic medium	Sandy loam	35	60	80
c	mesic poor	Silt loam	30	80	100
d	mesic medium	Silt loam	25	85	125
e	subhygric rich	Silt clay loam	15	110	150

5.2.1.3 Linking Tree Growth with Forest Hydrology

The linkage between the FORECAST and ForWaDy models underpins the operation of FORECAST Climate. This linkage is based upon the iterative sharing of information between models through the creation of feedback loops (see Figure 20). One challenge is the fact that the ForWaDy model operates on a daily time step (since this is the relevant interval for many hydrological processes), whereas FORECAST calculates productivity on a yearly time step. The latter model thus provides annual estimates of the key variables used by ForWaDy. These are listed in Table 13. ForWaDy output in turn is provided to FORECAST as a series of annual summaries of soil and forest floor moisture conditions, and cumulative measures of water stress for trees and plants.

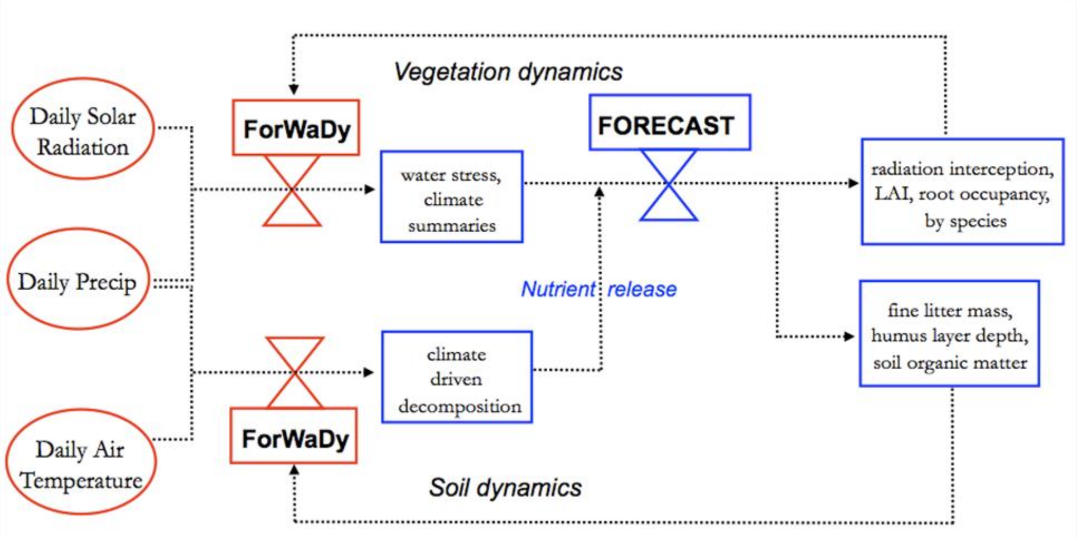

Figure 20. A schematic diagram illustrating the feedback loops established to facilitate the linkage of FORECAST and ForWaDy.

Table 13. A list of vegetation and soil condition variables passed from the forest growth model (FORECAST) to the hydrological model (ForWaDy).
The function of each variable in ForWaDy is also described.

FORECAST	ForWaDy	
Variable	**Receiving variable**	**Function**
Canopy light interception	Canopy radiation interception	Drives species specific transpiration
Foliage biomass	LAI[1]	Canopy interception
Fine root biomass	Lateral root occupancy	Soil water uptake capacity within a specific soil layer

FORECAST	ForWaDy	
Variable	**Receiving variable**	**Function**
Tree age	Rooting depth	Soil water uptake capacity from vertical soil layers
Fine litter mass[2]	Litter mass	Litter layer moisture content
Humus mass	Humus depth[3]	Humus layer water holding capacity

[1] Leaf area index is estimated using a species-specific conversion factor.

[2] Fine litter mass includes foliage, bark, and fruit (cone) litter types.

[3] Humus depth is estimated from humus mass, based on a parameter that defines the proportion of new humus transferred to non-surface layers and an estimate of surface humus bulk-density.

5.2.1.4 Accounting for Climate Impacts on Tree and Plant Productivity

The impact of climate on tree growth and ecosystem development in FORECAST Climate is focused, in part, on their relationship to temperature and water stress. These relationships are represented using curvilinear response functions, simulated on a daily time step and summarized annually. The temperature response functions (see Figure 21) encapsulate the multiple and complex physiological growth processes governing the response of trees and understory growth to mean daily temperature. The relative effect of temperature as a limiting factor on tree growth is captured annually through the sum of daily values. The positive effect of a lengthening growing season can also be represented with this approach. Note, however, that increases in summer temperatures may not necessarily have a positive impact on annual growth rates (Wilmking et al. 2004; see Figure 21).

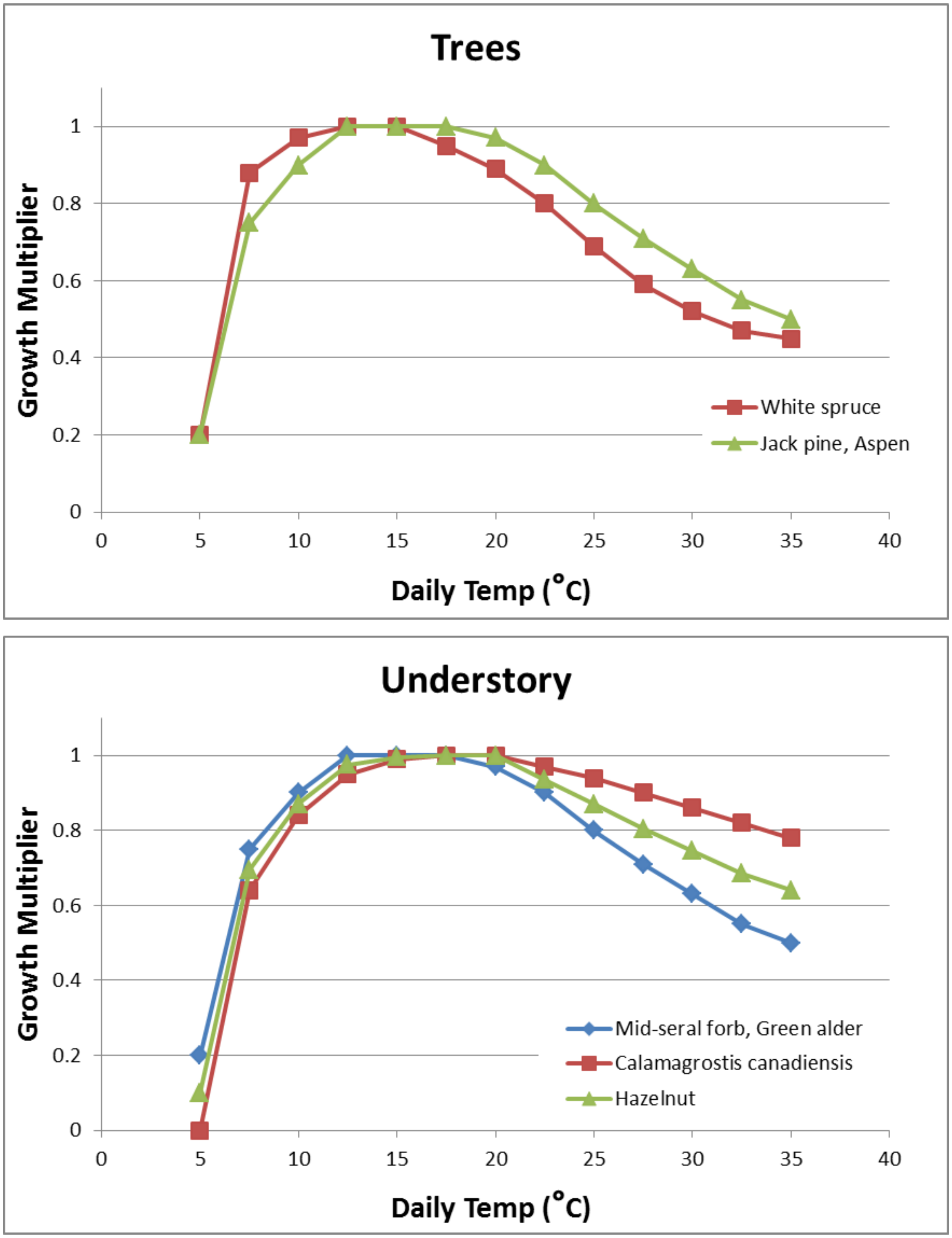

Figure 21. Temperature response functions used for trees (top panel) and understory (bottom panel) in the Kearl Lake project.

The effect of moisture availability on plant growth rates in FORECAST Climate is simulated by ForWaDy and calculated as the Transpiration Deficit Index (TDI, see Chapter 3 for details). The daily TDI value represents the degree to which a tree species was able to meet its energy-driven transpirational demands; a higher TDI value indicates more moisture stress. As the TDI increases, plants close their stomata to conserve water and there is an associated reduction in photosynthetic production (see McDowell et al. 2008). An evaluation of alternative TDI growth response curves based on tree ring chronologies (see Seely and Welham 2010) indicated that a negative exponential curve best reflected the effect of TDI on daily and annual productivity (Figure 22).

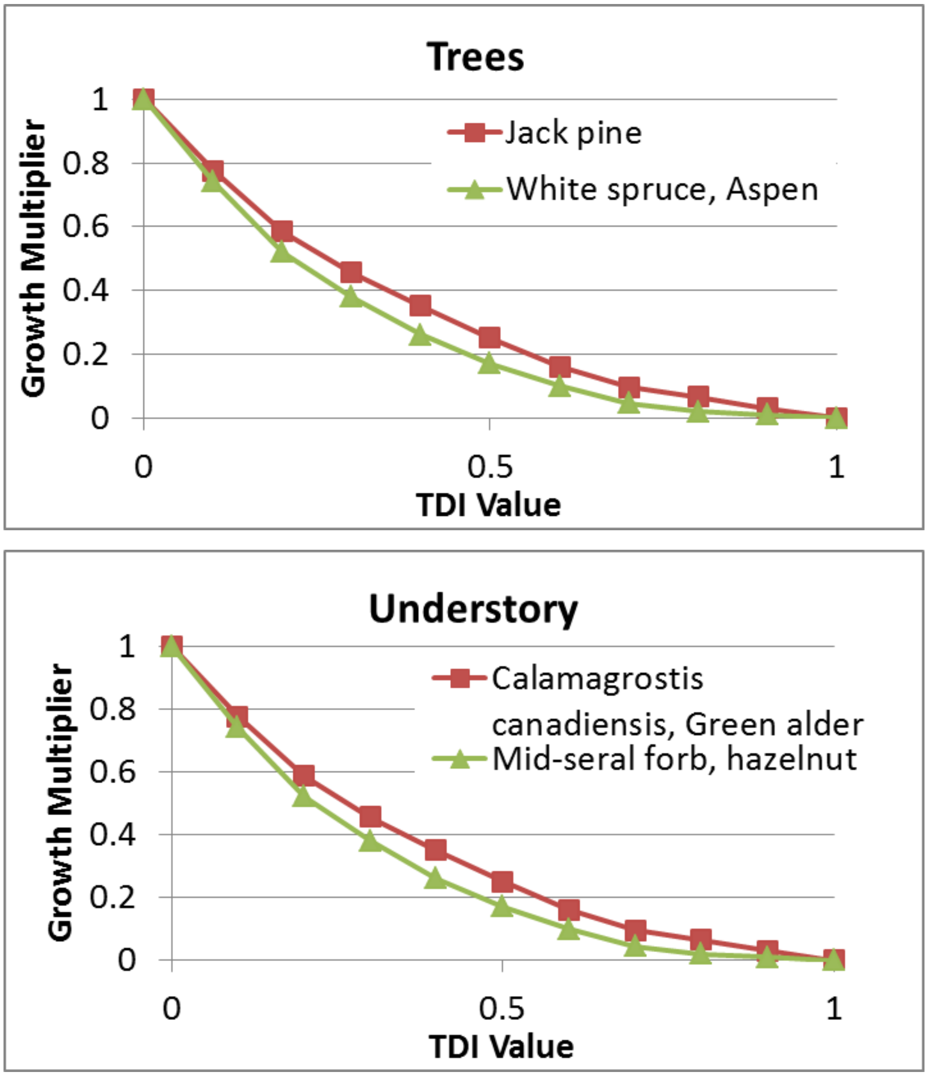

Figure 22. TDI response functions used for trees (top panel) and understory (bottom panel) in the Kearl Lake project.

The temperature and moisture response functions are incorporated into FORECAST Climate through their inclusion in a climate response index function (CRIgrowth). The CRIgrowth function is first calculated daily as the product of the temperature multiplier (Figure 21) and the TDI multiplier (Figure 22), and then summed over the year to create an annual index. Two types of CRIgrowth values were calculated. First, a climate-normal growth value (normal CRIgrowth) was determined using a 30-year (1975 to 2004) historical climate data set from the Fort McMurray, Alberta weather station. The process of determining a ‘normal’ value for CRIgrowth involves calculating a CRIgrowth value for each year of the historical climate data set and then calculating an average value for the climate response index (normal_CRIgrowth) over the 30-year period. The second type of CRIgrowth (current_CRIgrowth(i)) is calculated during an actual simulation, for each year, i. A weighted adjustment value is then derived using the normal_CRIgrowth value as the comparative standard (see equation below).

The potential growth rate (based on light and nutrient availability) in a given year is multiplied by the weighted climate response index to yield the actual annual growth rate in year, i:

$$\text{Annual growth rate}(i) = \text{potential growth rate}(i) \ast$$
$$(\text{current\_CRIgrowth}(i) - \text{normal\_CRIgrowth}) / \text{normal\_CRIgrowth}$$

where:

potential growth rate(i) = expected growth based on light availability and site quality

current_CRIgrowth(i) = the climate response index for a given year, i

normal_CRIgrowth= average climate response index based upon long-term historical climate data

In addition to the changes in growth, climate variability can also induce mortality events (Daniels et al. 2011). Climate-induced mortality has been demonstrated in aspen (Hogg et al. 2008) and white spruce (Wilmking et al. 2006). Hence, in addition to a reduction in tree growth from moisture limitation (Figure 22), a stand-level mortality algorithm was built into FORECAST Climate as a function of severe moisture stress (as determined from the TDI value). A TDI = 0.35 was used as the mortality threshold (see Figure 27, for an illustration of the distribution of TDI values). When a given TDI value exceeded the threshold in a given year, a species-specific mortality rate was imposed on the population (see Table 14). The mortality rate for a given species was derived by running FORECAST Climate using historical climate data and comparing growth and yield metrics in two scenarios. In one case, growth and yield was calculated with the addition of the mortality function, and in the other case, without the mortality function. Mortality rates were deemed acceptable when their respective growth and yield data were within an average of 10% across a 100-year simulation period. Rates were then evaluated for accuracy by comparison to estimates provided in Hogg et al. (2008), Michaelian et al. (2011), and Wilmking et al. (2004, 2006). Mortality rates for understory species were set at either 0% or 10% since no information on this parameter is available from published sources.

Table 14. Percentage of trees killed (mortality rate) for each plant species simulated under two mortality scenarios.

Species	No mortality	Mortality
Jack pine	0%	10%
Aspen	0%	15%
White spruce	0%	7.5%
Calamagrostis canadensis	0%	10%
Mid-seral forb	0%	10%
Hazelnut	0%	10%
Green alder	0%	10%

5.2.1.5 Accounting for climate impacts on decomposition rates

The decomposition of dead organic matter (litter and soil organic matter) in FORECAST is represented by grouping litter created through the death of specific biomass components into different litter types, each with defined mass loss rates (see Kimmins et al. 1999). In FORECAST Climate, these litter decomposition rates and their associated nutrient mineralization rates are adjusted based on soil moisture content and temperature. A base mass loss rate is provided for each litter and humus type (parameterized from field or literature values) that reflects both the quality of the litter and a ‘normal’ climate regime. These mass loss rates are then modified within the model to account for the effect of climate, as follows.

Temperature

A variety of techniques have been developed to quantify the effect of temperature on decomposition. The most common are simple calculations of weight loss using litterbags, field soil respiration measures (either by eddy covariance or gas chambers), and laboratory or ^{14}C studies. Consumption of dead organic matter by heterotrophic microbes and fungi is generally faster in warmer environments (Chen et al. 2000, Gholz et al. 2000, and references therein).

Many studies use the Q10 equation to describe effect of temperature on organic matter decomposition rates:

$$Q10 = (R2/R1) \wedge (10/(T2-T1))$$

where:

R1 = mass loss rate at temperature 1 (T1 °C)

R2 = mass loss rate at temperature 2 (T2 °C)

In FORECAST Climate, the impact of temperature on the decomposition rates of litter and humus is simulated based on the Q10 equation. For the runs in the Kearl Lake area, a value of 2 was used for the Q10 since this is typical for decomposition studies (Gholz et al. 2000, Zhou et al. 2008). The effect of this value on relative mass loss rates is illustrated in Figure 23.

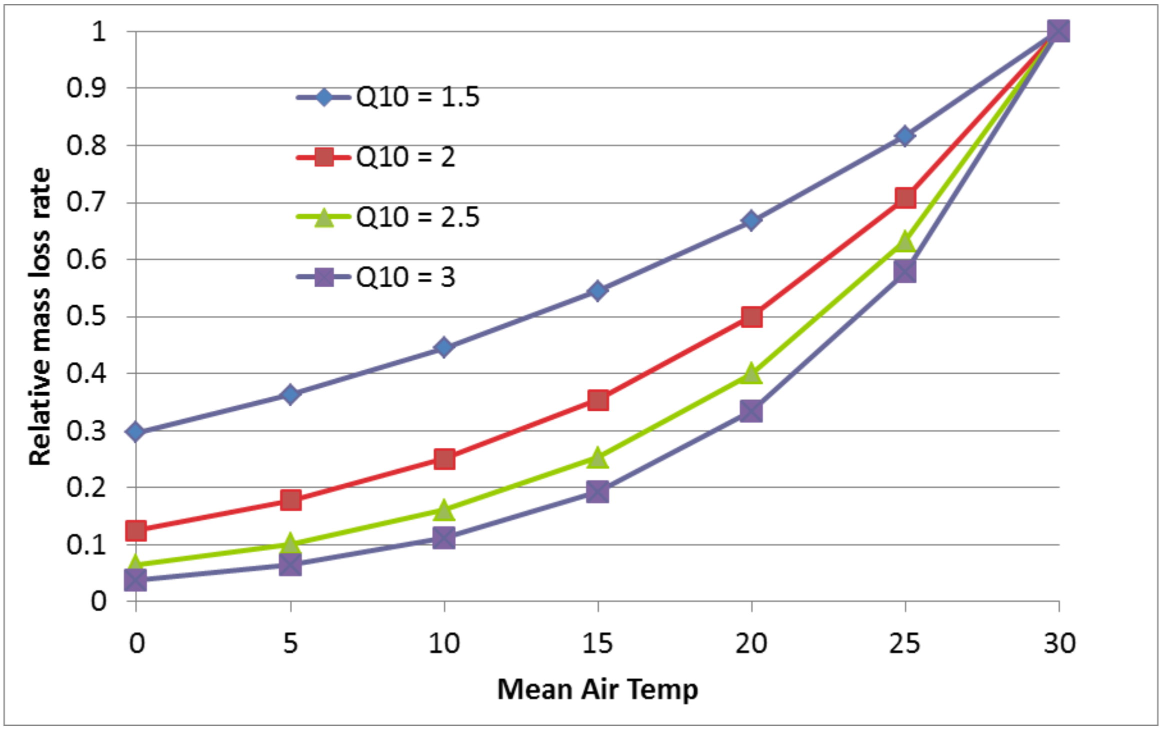

Figure 23. Illustration of the effect of a range of Q10 values on the calculation of a relative mass loss rate as a function of mean daily air temperature using the Q10 equation.

Precipitation and Litter Moisture Content

Precipitation as a factor in decomposition rates has received much less attention than temperature despite the fact its importance has been clearly demonstrated (e.g., Chen et al. 2000, Ise and

Moorcroft 2006, Prescott et al. 2004). A key feature of these studies is that decomposition rates are directly correlated to precipitation until a threshold is reached, after which there is little or no additional effect.

A daily relative mass loss rate is calculated within FORECAST Climate for each litter and humus type using a curvilinear function based upon simulated moisture content in the litter and humus layers (Figure 24). Litter moisture content is used to drive mass loss rates for forest floor litter types while humus moisture content is used for any below-ground litter and humus.

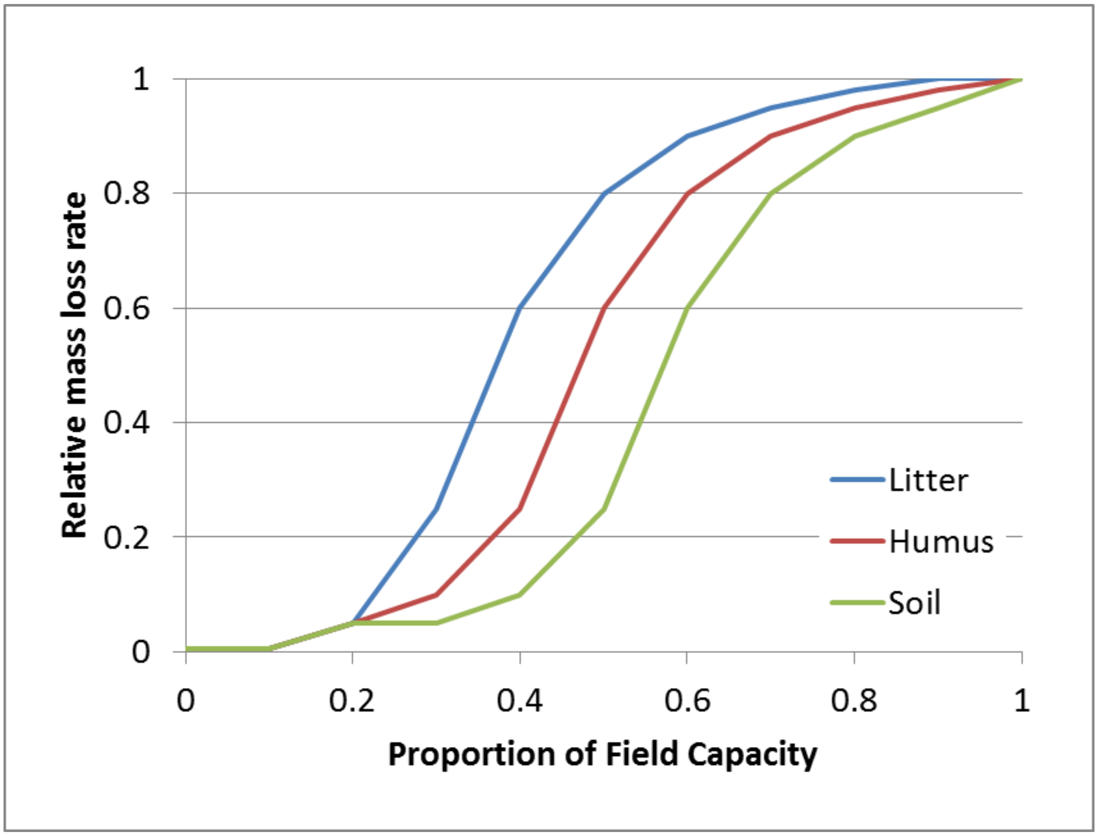

Figure 24. Response curves of the effect of daily moisture content (as a proportion of the Field Capacity value) on the relative mass loss rate of litter and humus.

FORECAST Climate employs a similar method for scaling decomposition rates to climate as was used for scaling annual growth rates (see Chapter 4). The temperature-limited relative mass loss rate (Figure 23) is multiplied by the daily moisture-limited rate (Figure 24) for each litter and humus type, j, to produce a daily decomposition climate response index, CRIdecomp, that is then summed over the year to provide an annual index. A normal_CRIdecomp value is calculated for each litter and humus type based on historical climate data using the same approach described in Chapter 4. A second type of CRIdecomp (current_CRIdecomp(i)) is calculated during an actual simulation, for each year, i. A weighted adjustment value is then derived using the normal_CRIgrowth value as the comparative standard (see equation below).

The base mass loss rate of a given litter or humus type, j, is multiplied by the weighted climate response index to yield the actual mass loss rate in year, i (Annual mass loss rate(i,j)):

$$\text{Annual mass loss rate}(i,j) = \text{base\_ rate}(j) * (\text{current\_CRIdecomp}(i,j) - \text{normal\_CRIdecomp}(j)) / \text{normal\_CRIdecomp}(j)$$

where:

base_rate(j) = expected mass loss rate for each litter and humus type, j

current_CRIdecomp(i,j) = climate response index for each litter and humus type, j, for the current year, i

normal_CRIdecomp(j) = average response index for each litter and humus type, j, based upon long-term historical climate data

5.2.2 *Climate Change Scenarios*

To simulate the effects of a changing climate, five climate-change models and associated emissions scenarios (Table 15) were selected. A complete description of their derivation and application is provided in Chapter 3.

Table 15. Climate models and scenarios selected to simulate climate change in 2020, 2050 and 2080.
See Appendix for values of monthly modifiers for minimum temperature, maximum temperature and precipitation.

Model	**Scenario**
CCSRNIES	A1 F1
CGCM2	B23
HADCM3	A2 A
HADCM3	B2 B
NCARPCM	A1 B

5.3 Results and Discussion

5.3.1 *Tree Productivity*

Stands initiated under current climatic conditions (in year 2011) are predicted to experience enhanced long-term productivity (to year 2111) under a changing climate regime, as compared with the growth that would have occurred if historical climatic conditions been maintained over the next 100 years (Figure 25). Increases in productivity due to climate change become evident at around 2030 and continue to increase over subsequent years. By year 2111, average stemwood productivity (either in terms of biomass or volume) was 33%, 30%, and 42% greater under climate change for jack pine, aspen and white spruce, respectively (Figure 25). There was a substantial range among the GCM scenarios in their projections of stemwood growth. The minimum projection, however, was always greater than that derived from the historical climate data (Figure 25).

The highest stemwood biomass projection in jack pine and aspen always occurred under the A1F1 emissions scenario. This scenario was associated with the highest increases in temperature (see Figure 13). In addition, mean annual precipitation and growing season precipitation were both projected to be higher in the 2080s, and in amounts that exceeded all other emission scenarios (Figure 14). In the case of white spruce, the A1B scenario generated the highest biomass productivity. This scenario projects relatively cooler temperature in the Fort McMurray region with somewhat drier annual and growing season precipitation than the median climate change scenario (HadCM3 B2(b); see Chapter 3).

In general, forest productivity in northern latitudes is temperature-limited. Climate in the Fort McMurray region is continental semi-arid to sub-humid, with cool summers and cold winters. Mean daily summer and winter temperatures are 13°C and -12°C, respectively (Beckingham and Archibald 1996). The growing season starts around late April and ends in early October. However, frosts can occur as late as mid-June and as early as mid-August, a period of only 8 weeks. It appears therefore that the increase in productivity under climate change for stands initiated in 2011 is a consequence of ameliorating conditions. All GCM scenarios predict warmer growing season and mean annual temperatures (see Chapter 3). This suggests an increase in the frost-free period along with warmer soil temperatures. Most GCM scenarios also predict increases in mean annual precipitation (Figure 14A) though with a relatively drier growing season (Figure 14B). Mean annual precipitation averages about 400 mm in the Fort McMurray region and summer moisture deficits are not unusual, particularly in August. It appears then that tree productivity in the region may be enhanced through much of the 21st century as a result of improvement in the thermal regime (and potentially an overall increase in available moisture) that more than compensates for any negative impact associated with growing season moisture limitations. Girardin et al. (2008) reported a similar finding when they used the process model, STANDLEAP, to simulate the impact of climate change on radial growth in jack pine, aspen, and black spruce, growing in Manitoba.

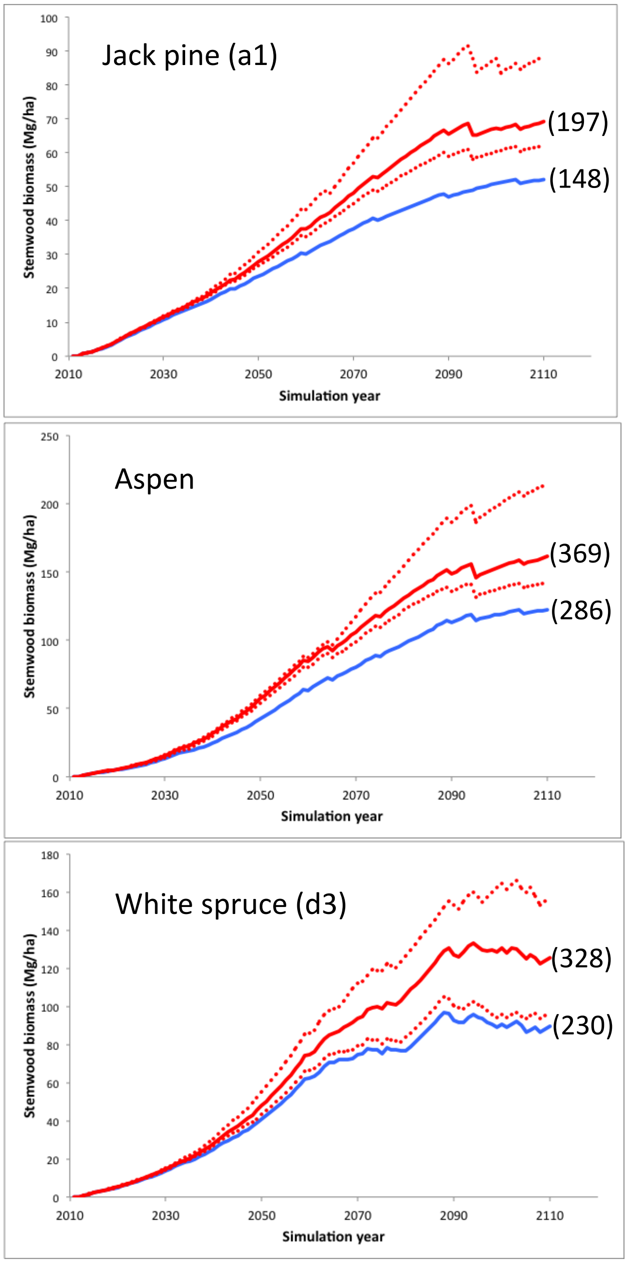

Figure 25. Projected stemwood biomass in jack pine (ecosite a1), aspen (ecosite d1), and white spruce (ecosite d3) for stands initiated in year 2011 and growing subsequently under current climatic conditions (blue solid line), or the average stemwood biomass derived from growth under climate change projections for 5 GCM scenarios (red solid line).
Dotted lines are the associated maximum and minimum stemwood biomass estimates from the five scenarios. Brackets denote projected gross volumes (m^3 ha^{-1}) after 100 years growth (to year 2111). See text for further details.

How the future temperature and precipitation regimes in high latitude forests might promote long-term tree productivity can be determined from an examination of trends in the climate response index (CRIgrowth). CRIgrowth is calculated as the product of a temperature multiplier and the transpiration deficit index (TDI) multiplier (Figure 21 and Figure 22, respectively), and which then functions as a growth modifier (see above). The higher the CRIgrowth, the more favorable are conditions for growth. A plot of CRIgrowth for the three tree species under the A1F1 emission scenario, for example, was consistently higher than the values calculated on historical climate data in all years beyond the 2030s (Figure 26). In jack pine, this trend increased until the 2070s and then leveled off, though in aspen and white spruce, the differences continued to increase. The TDI values for jack pine under climate change were consistently higher than TDIs from historical data (Figure 27A). This indicates that there was less water available to satisfy tree demands under climate change than occurred historically. This is likely why CRIgrowth for jack pine is projected to level off (Figure 26A). TDI values in aspen and spruce were very similar between historical values and the A1F1 emissions scenario (Figure 27B, C) indicating essentially no significant increase in moisture stress associated with climate change. Greater snow packs derived from increased winter precipitation in the climate change scenarios help to offset the greater transpiration demand observed in the climate change scenarios (data not shown).

The soils underlying the spruce and aspen stands (d ecosites) have greater clay content and less coarse fragment content relative to soils under jack pine. These attributes allow for greater soil water storage and a greater capacity to store soil water generated from snowmelt. In contrast, the jack pine, growing on soils with poor water holding capacity, relies more upon summer precipitation to satisfy moisture demands. Overall the higher CRIgrowth values (Figure 26) and, hence, increases in productivity (Figure 25) in the three tree species must have been due to the higher projected temperatures. Temperature impacts on soils will be discussed below.

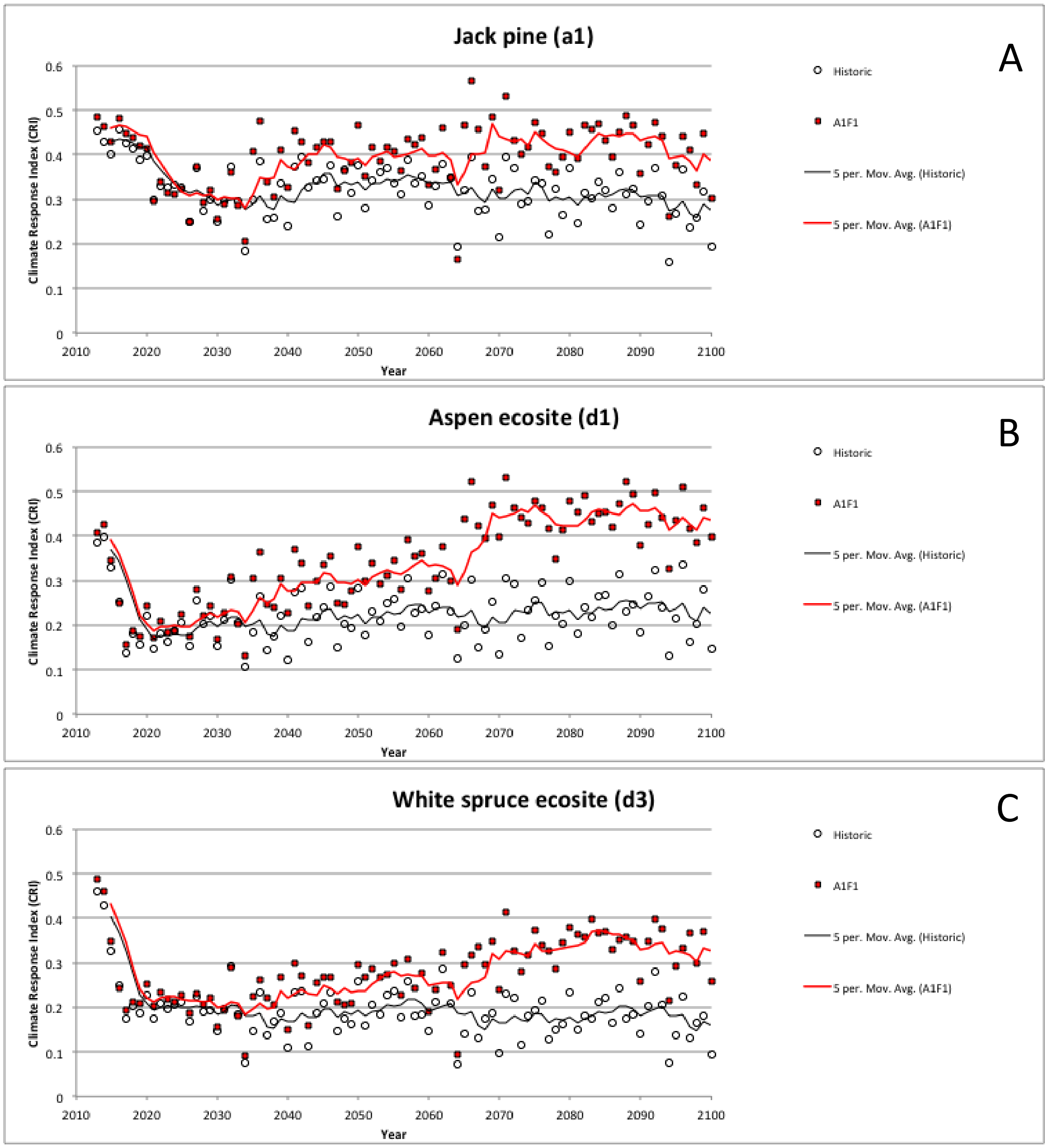

Figure 26. Climate response index (CRI) for jack pine (A), aspen (B), and white spruce (C), planted in year 2011, and derived from historical climate data (open circles) or the A1F1 emissions scenario (filled circles).
The corresponding 5-year moving averages are also shown. See text for further details.

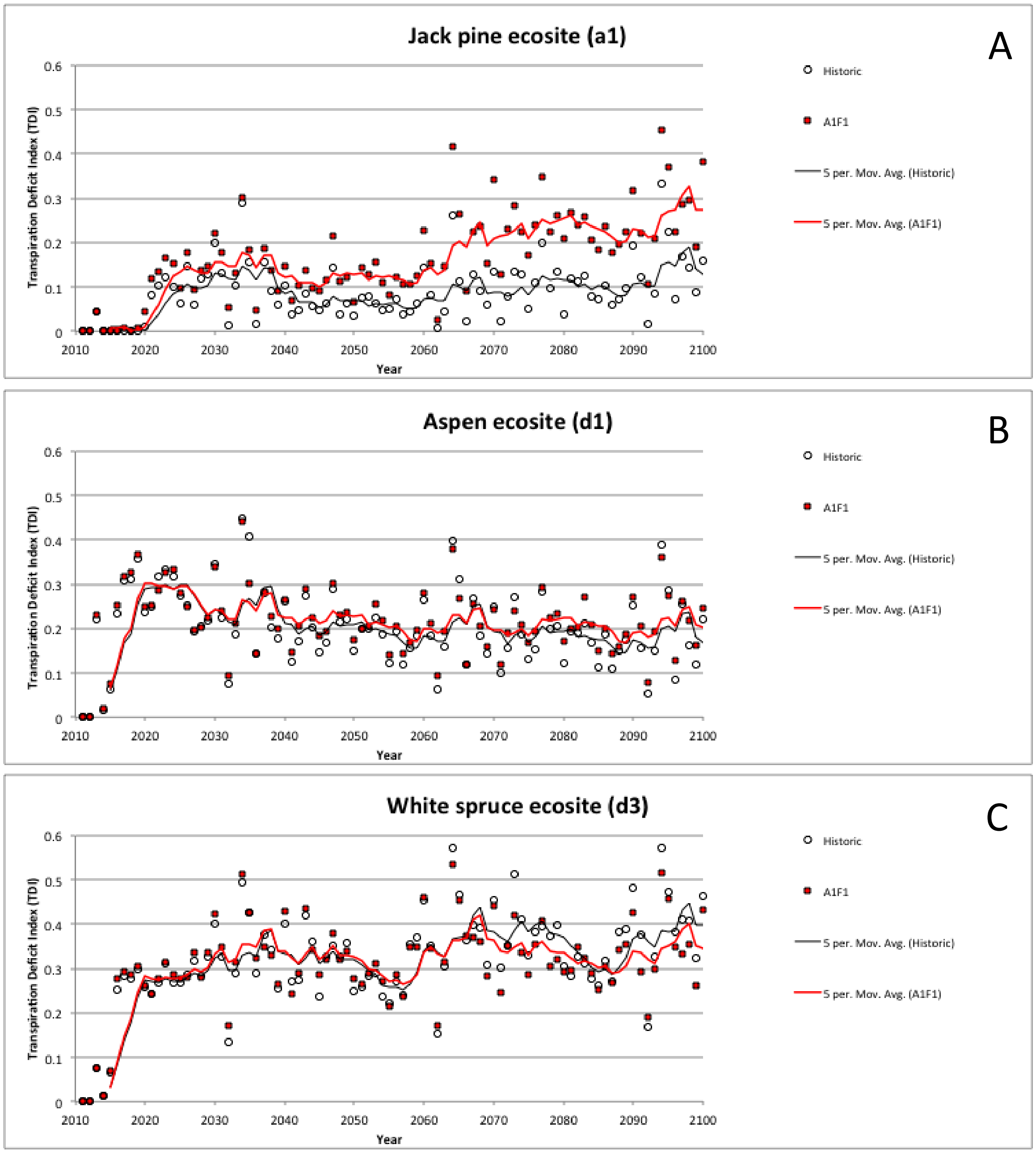

Figure 27. Transpiration deficit index (TDI) for jack pine (ecosite a1; A), aspen (ecosite d1; B), and white spruce (ecosite d3; C), planted in year 2011, and derived from historical climate data (open circles) or the A1F1 emissions scenario (filled circles). The corresponding 5-year moving averages are also shown. See text for further details.

5.3.2 ***Soils***

Forest productivity in boreal forests is significantly limited through the negative impact of low soil temperatures on heterotrophic decomposition, nutrient availability and root growth (Bonan and Van Cleve 1992, Paré et al. 2006). Van Cleve et al. (1990), for example, demonstrated through a soil warming experiment in a cold black spruce forest that increased soil temperature led to increased microbial activity and increased root uptake of nitrogen. FORECAST Climate accounts for the effect of changes in soil temperature on organic matter decomposition rates through the use of the Q10 function (described above) to adjust mass loss rates (see Figure 23).

The projected impact of climate change on organic matter decomposition rates can be evaluated through an examination of the calculated decomposition climate response index (CRIdecomp). The CRIdecomp values calculated for the different climate change scenarios showed a trend that parallels the increase in growth. Figure 28 provides an illustrative example from ecosite d1 (aspen); similar trends were observed in the other ecosites. CRIdecomp under the A1F1 scenario was similar to the trend based on the historical climate data for about 15 years following stand initiation (Figure 28A). Thereafter, the indices diverged and the climate change CRIdecomp continued to increase for the remainder of the simulation period (through 2111). This indicates a net positive effect of temperature and/or precipitation on organic matter decomposition, as indicated in the CRIdecomp values. Enhanced decomposition in turn, was reflected in higher nitrogen release rates (Figure 28B). Since there is a positive relationship between temperature and decomposition rate (Adair et el. 2008) one benefit of a warmer temperature regime then may be to ameliorate constraints on stand productivity in these high latitude ecosystems.

5.3.3 ***Understory Dynamics***

Understory vegetation can have an important impact on ecosystem processes such as nutrient cycling, and patterns of overstory development, stand succession, and long-term productivity (Kolari et al. 2006, Messier et al. 1999, Nilsson and Wardle 2005, Wardle et al. 2004, Zavitkovski 1975). In addition, the understory is valuable to wildlife as a source of food, shelter, and protection from predators (understory development as an index of habitat suitability is considered in a subsequent section).

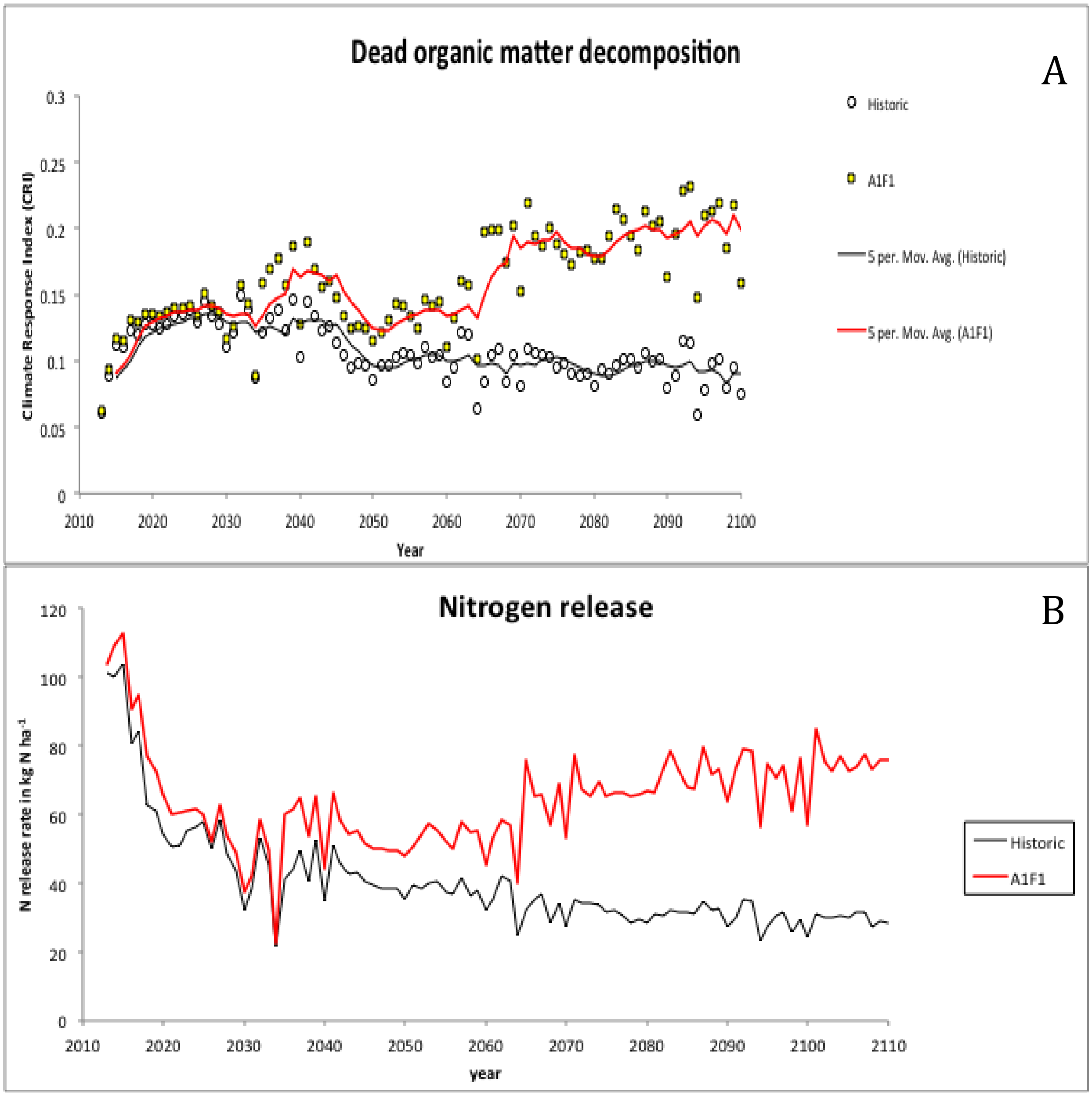

Figure 28. Climate response index (A) and nitrogen release rate (B) for an aspen-dominated ecosite (d1), planted in year 2011, and derived from historical climate data (open circles and grey line) or the A1F1 emissions scenario (filled circles and red line). Solid lines in panel A are the 5-year moving averages. See text for further details.

In general, understory development reflects below-canopy light levels. After a stand-replacing disturbance, light levels are high and the understory is often dominated (in terms of biomass) by shade-intolerant, fast-growing pioneer species. During canopy closure, light levels below the canopy decline. At this point, overall understory abundance depends on the degree of light attenuation. An overstory canopy dominated by white spruce tends to reduce overall light levels during the growing season to a greater extent than aspen. This is largely because of higher light levels in aspen during the leaf-off period in spring and fall (see for example, Constabel and Lieffers 1996). Model simulations using historical climate data support this general pattern. Total understory biomass in aspen and spruce tended to reach maximum values (of roughly 7 Mg ha^{-1}) about 10 years after stand initiation (Figure 29B, C) and then declines thereafter. In the case of aspen, the understory leveled off at roughly 2 Mg ha^{-1}, whereas in spruce it declined over the next 40 years to a very low level. There was a different trend in jack pine. In this case, understory biomass increased rapidly in the first 20 years following stand initiation and then persisted thereafter (Figure 28A). The most likely explanation is that pine often establishes on coarse textured soils (Beckingham and Archibald 1996) where tree productivity is constrained by available soil moisture. Stands therefore tend to be more open-grown, and with the lower leaf area, light levels remain relatively high. Vigorous tree growth, however, tends to shade out all understories regardless of the tree species (Bartemucci et al 2006).

Under climate change, tree productivity is enhanced (Figures 25, 29). As a consequence, light attenuation will be more severe resulting in suppression of the understory. This is most evident in jack pine (Figure 29A) though it also occurs in aspen but to a lesser extent (Figure 29C). The level of understory suppression in spruce was unchanged and thus remained high (Figure 29C). Taken together, these results highlight the complex interrelationship of the overstory and understory populations. A heavily stocked and/or fast-growing overstory is likely to suppress the understory following canopy closure. Hence, a vigorous understory may develop early in stand development but it can be maintained only at the expense of overstory development.

5.3.4 *Development of Habitat Suitability Indices under Climate Change*

In previous work, habitat suitability indices (HSIs) were derived for 10 species common to the Fort McMurray region (Welham 2010). Projections of HSI development were made over a 100-year time period but without any consideration for climate change. Given that climate change is projected to modify patterns of stand productivity (Figure 25) and development (Figure 29), Figure 30 illustrates its relative impact on habitat suitability in five of the ten species and three ecosites, a1, d1, and d3 (results were not dissimilar for the remaining species) using the A1F1 emission scenario. Model projections indicated that habitat suitability under climate change would be improved overall, relative to values derived using the historical climate regime (Figure 30).

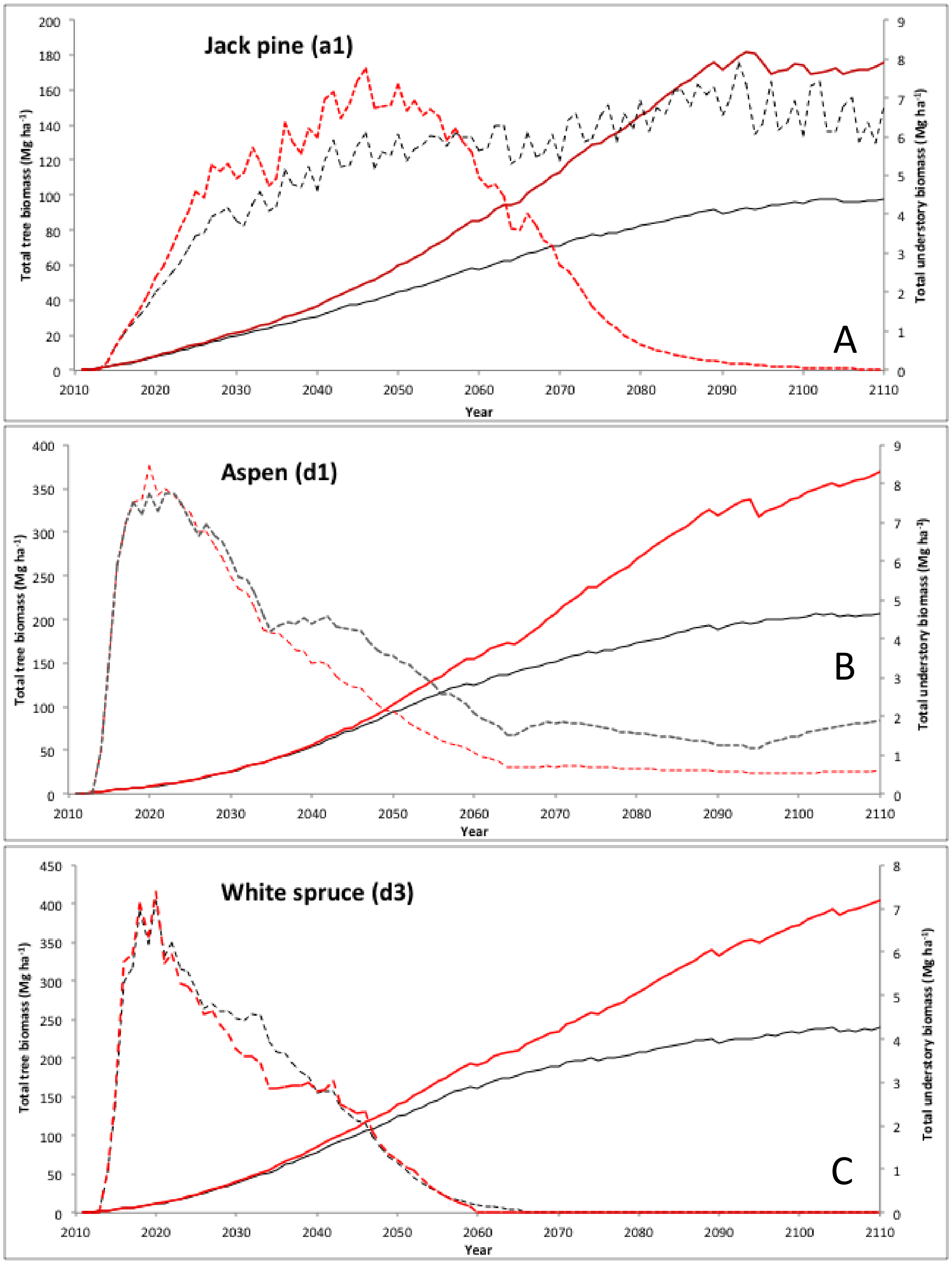

Figure 29. Total tree (solid lines) and understory (dashed lines) biomass for jack pine (ecosite a1; A), aspen (ecosite d1; B), and white spruce (ecosite d3; C), planted in year 2011, as projected under historical climate data (grey) or the A1F1 emissions scenario (red).

The greatest improvement in the HSIs was for the d1 (aspen) ecosite and the least in the d3 (white spruce) ecosite. The latter result is likely because, aside from improved tree productivity, there was little change in understory biomass or its dynamics (Figure 29C). In the case of the aspen ecosite, much of the increase was dominated by improvements in snowshoe hare and lynx habitat, and to a lesser extent, red-backed vole habitat (Figure 30B). Both snowshoe hare and red-backed voles are dependent on low-lying vegetation (see Welham 2010) and yet understory biomass in the A1F1 scenario was actually lower than that projected from historical climate data (see Figure 29B). The most likely explanation is that enhanced tree growth under climate change (Figure 29B) reduced below-canopy light levels enough to suppress height growth in understory shrubs (the latter are a critical feature of hare habitat; see Welham 2010) but still maintain sufficient biomass to satisfy food and cover requirements. Snowshoe hares are an important food source for lynx and the HSIs for the latter incorporate the HSI values for hare. Consequently, there is a consistent and close correlation between the HSI values for these species (note that the Fisher HSI is correlated to red-backed vole abundance also; see Welham 2010), as reflected in Figure 30B.

For the a1 ecosite, the HSI values were relatively higher under the A1F1 scenario (as compared to when the historical climate data were used) in all five species during early stand development (Figure 30A). This was likely because of the greater understory biomass during this period (Figure 29A). However, the difference in the HSI values from the historical climate data decreased thereafter (Figure 30A), a trend that reflects the decline in understory abundance (Figure 29A).

HSI values for all species except moose tended to be higher under the average of all climate change scenarios as compared to the values derived using the historical climate data (Figure 31). In the case of moose, there was very little overall difference in the HSIs. Climate change had a much more positive impact on snowshoe hare habitat (and thus lynx habitat) in the a1 ecosite (Figure 31A), and somewhat less of an impact in the d3 versus d2 ecosites (cf. Figure 31B,C). The improvement in habitat for the remaining species was about the same across the three ecosites.

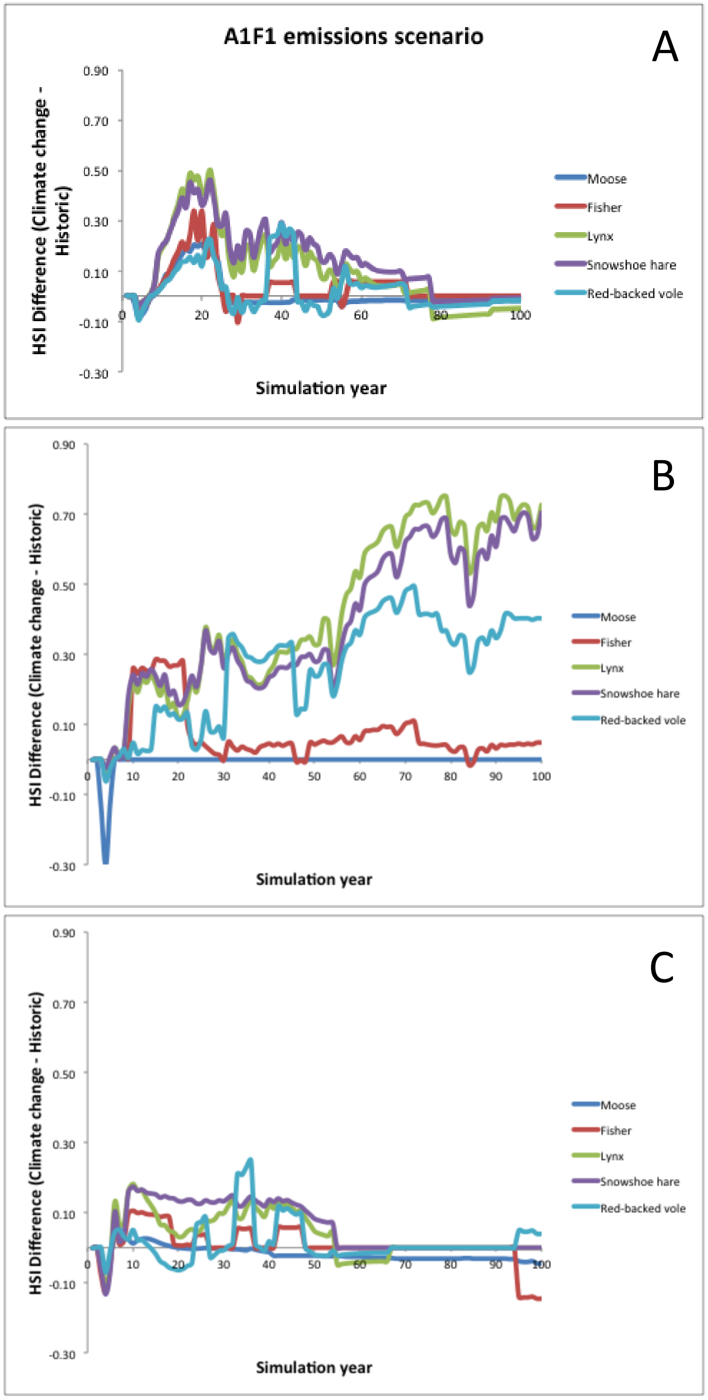

Figure 30. Differences in the habitat suitability index (HSI) from five species for ecosite a1 (jack pine; A), d1 (aspen; B), and d3 (white spruce; C).
Stands were planted in year 2011 and HSIs calculated from growth under the A1F1 emission scenario and using historical climate data. Note that a given HSI varies between 0 and 1.

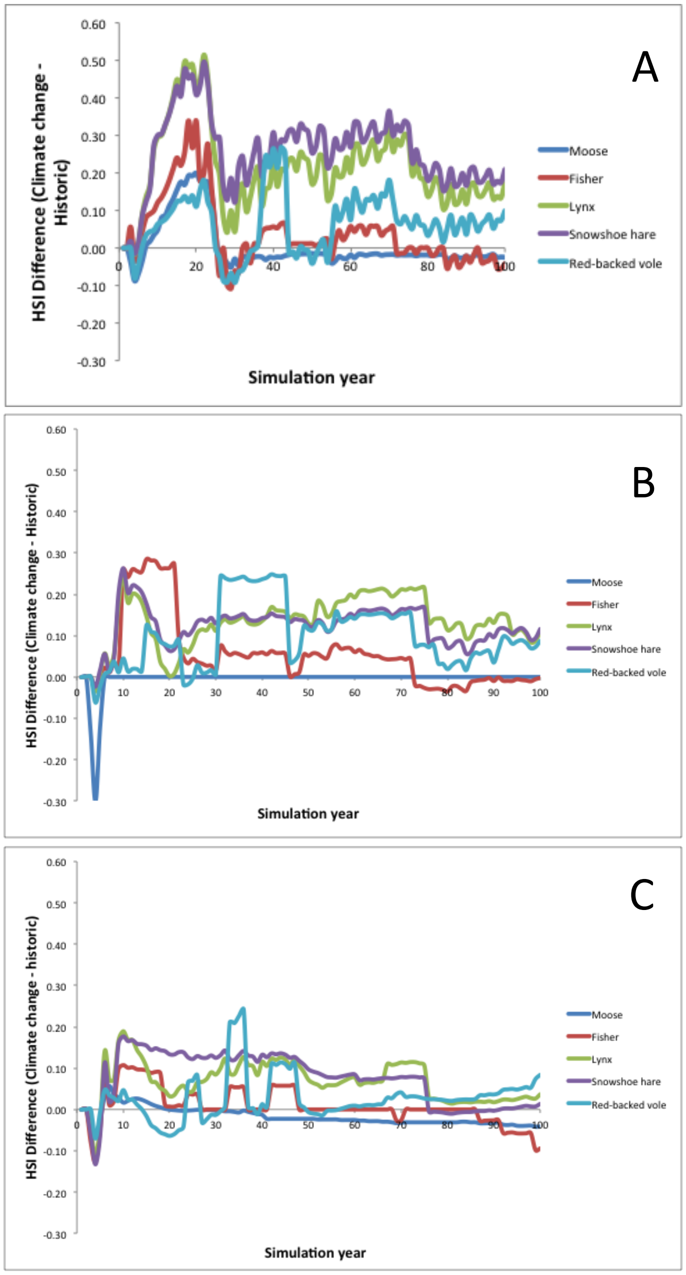

Figure 31. Differences in the habitat suitability index (HSI) from five species for ecosite a1 (jack pine; A), d1 (aspen; B), and d3 (white spruce; C).
Stands were planted in year 2011 and HSIs calculated from growth under the full range of climate change scenarios and using historical climate data (see text). HSI values under climate change were therefore the average from all scenarios. Note that a given HSI varies between 0 and 1.

5.3.5 *Management Implications*

Large-scale analyses of the impact of climate change on species distribution, often predict range contractions and migration into areas where species are not present under current climate conditions (see, for example, Coops and Waring 2011, Hamann and Wang 2005 and McKenney et al. 2007). Typically, these models draw inferences from general correlational relationships with climate and without explicit consideration of the non-climate mechanisms or processes that dictate the presence or absence of a species (see Chapter 4) or that drive productivity (this Chapter). Climate is an important determinant of the broad-scale distribution of tree species (McKenney et al. 2007) but at a local level its effects can be mediated through soils, the presence of other plant species (where effects can be positive or negative), herbivores, diseases, insects and fire (Lo et al. 2010; see below for further discussion). Results at local levels are therefore likely to be very different from regional analyses.

In this case, model simulations indicated enhanced productivity in the three tree species that was driven primarily by the projected increases in mean annual temperature associated with climate change. In more southerly regions of Alberta, moisture is the factor most limiting to both tree distribution and productivity (Cerezke 2009) but at higher latitudes these may be limited more by temperature than precipitation (Cerezke 2009, McKenney et al. 2007, and references therein; though see Rweyongeza et al. 2007). Although moisture deficits tended to be higher under climate change, at least during the growing season, they were not sufficient to offset the benefits of warming in this cool, continental climate (see also Girardin et al. 2008). Nevertheless, our analysis does indicate that over time, regenerating these tree species may become problematic (see Chapter 4).

These results suggests a number of management responses within the context of oil sands reclamation that can reduce risk, help mitigate carbon emissions (modified from Cerezke 2009) and retain habitat features, at least for some species.

1. **Minimize the forest cover removed as part of mine operations**

   Typically, a vast majority of existing vegetation is removed from the mine footprint in preparation for mining. Carbon emission sources include the fossil fuel consumed by clearing activities and possibly in manufacturing if wood products are generated. Large amounts of carbon might also be released if the dead organic matter pools are then subject to enhanced decomposition (see, for example, Welham et al. 2011). Decay of discarded wood products would constitute a short- to medium-term carbon source. Retention of forest cover improves the carbon balance and, depending on its areal extent and spatial configuration, can also serve as refugia for wildlife on the mine footprint.

2. **Return forest cover as soon as is practicable**

   Typically, a majority of reclamation is deferred until mine closure activities are well underway (see, for example, Welham 2010). As a consequence, carbon accrual occurs only minimally and the development of significant amounts of habitat is delayed for many decades (Welham 2010). Since forest productivity under climate change is enhanced, however, this translates into higher carbon sequestration and improved habitat suitability as compared to the reference case (the historical climate regime). Returning forest cover as soon as is practicable serves to leverage the benefits from improved productivity.

3. Expand forest carbon sinks

Fertilizer is typically used in oil sands reclamation to improve early seeding survival and growth. Its application rate and duration (i.e., number of growing seasons it is applied), however, varies widely, depending on the mine operator. Adding fertilizer annually for 5 to 10 years after planting, particularly on poor sites, will promote both tree and understory productivity, and thus carbon storage and development of habitat attributes. Retaining and adding slash and other dead organic matter after land clearing will also increase carbon stores (at least temporarily) but more importantly create valuable habitat. Dead wood management is currently not standard operating practice but limited experimental trials at Suncor have provided evidence to support its benefits.

4. Encourage species mixtures over monoculture plantations

Our model simulations considered the impact of climate change from the perspective of resource availability only, and to simplify the analysis we did not include mixed-species assemblages (cf. Welham 2010). Conifer monocultures and extensive tracts of aspen-dominated forests, however, are vulnerable to outbreaks of insect defoliation (Hogg et al. 2002, 2005, Volney and Fleming 2000) and bark beetles (Carroll et al. 2003). Climate change is expected to increase the risk of pathogen outbreaks (Woods 2011). This will lead to reduced growth rates and associated tree mortality (Sturrock et al. 2011), and thus lower carbon storage. Snags and lying dead wood do represent positive habitat attributes for some species (pileated woodpecker, for example; see Welham 2010). For a majority of species, however, their habitat depends on live tree biomass.

Simulating the future dynamics of pathogen populations under changing environmental conditions and their potential impacts on host populations is complex, and fraught with difficulties (Woods 2011). From a practical perspective, however, planting tree species in mixtures or at the very least, reducing the areal extent of monocultures (creating a number of relatively small monoculture patches that are highly interspersed) may help mitigate risk, enhance forest resilience, and/or prevent large-scale pathogen outbreaks. Introduction of genetic strains with greater pathogen resistance may also be useful. Relaxation of seed zone restrictions can promote the crossbreeding of traits that confer pathogen resistance. Additionally, it may be prudent to consider planting species that are resistant to endemic insect species. The impact of changes in community composition on habitat quality is difficult to determine for many species. This is, in part, because their habitat requirements are poorly understood and/or their habitat suitability indices are based on generic structural attributes (see Welham 2010). There is a risk that a drastic shift in community composition could compromise wildlife species that have very specific habitat requirements.

5. Increase protection measures

Vigorous and healthy forest stands are key to reclamation outcomes. On an annual basis, insects and disease kill at least as many trees as fire. Surveillance technology needs to be deployed to address forest health and productivity issues, monitor abiotic and biotic agents for their potential to cause tree and forest damages, and tree and stand responses to disturbance events. Mine operators should develop and implement regular monitoring programs on their reclaimed areas. A unified reporting program across all mines would be useful for identifying potential issues before they become unmanageable. Control measures should be implemented as required and in a timely fashion.

6. Increase fire suppression capability

An increased risk of forest fires (both in frequency and severity) is predicted to occur with climate change. These changes in this disturbance regime will result in significantly greater releases of carbon as material is consumed, but can also generate rapid and pronounced shifts in community composition. An increase in fire frequency, for example, reduces average forest age, tends to favor species with attributes specifically adapted to fire (the serotinous cones of jack pine, for example) and selects against late seral species, such as white spruce. As a consequence, associated changes in habitat can be expected. Investment in fire protection capacity will reduce catastrophic CO_2 emissions, and help maintain forest cover and associated wildlife habitat attributes. One recommendation to mitigate risk and/or prevent large-scale pathogen outbreaks was to avoid monocultures (see point 4). In the case of conifers, intermixing with deciduous species also has the benefit of reducing fire risk since the latter are less prone to burning.

6 NEXT STEPS

The principal objective in Phase II was an evaluation of the impact of climate and climate change on reclamation success, as compared to the basecase analysis (no climate-related impacts) conducted in Phase I. Complexities in implementing model simulations and interpreting the proliferation of simulation output, however, meant that not all anticipated objectives could be satisfied within the funding cycle. Additional work required to complete Phase II objectives includes:

1. Project regeneration potential under climate change on actual oil sands reclamation materials. To date, regeneration parameters in the TACA model were derived from attributes in the soils underlying natural forests. Reclamation materials are very different both structurally and biochemically, and these differences are likely to be reflected in vegetation performance (in this case, regeneration success). Completing this component will also allow a direct link between the productivity runs conducted on reclaimed soils (see Chapter 5) and regeneration.
2. Establish a more rigorous analysis of the risks to ecosystem productivity from climate change. Historically, primary productivity in high latitudes is temperature limited, as a result of a short growing season, a relatively brief frost-free period, and cold soils. Overall, climate change acts to ameliorate many of these constraints with the result that average productivity is expected to rise through the 21st century (as Phase II illustrates). However, climatic variability is also increasing. The severity and frequency of inclement conditions, such as growing season moisture stress, could therefore compromise overall productivity as a result of stand-level mortality.

Under the current simulations, when a given transpiration deficit index (TDI) value exceeded the threshold (set at 35%) in a given year, a single species-specific mortality rate was imposed on the population. This approach may be overly simplistic, however, given that the physiological mechanisms underlying drought survival and mortality are complex and poorly understood (McDowell et al. 2008). Hence, a variety of methods to represent mortality should be considered.

3. Re-calculate the HSIs after including spatial metrics.

4. Provide a visual representation of HSI development both in space and time. Habitat suitability indices were calculated from EIA projections of the cumulative area reclaimed to a given ecosite type on the Kearl Lake mine footprint but they did not include parameters that required spatially explicit metrics. Seven of the 10 habitat suitability equations contain a component that accounts for the spatial proximity of potential disturbance agents (roads and permanent structures, for example). Disturbances within specified zones of influence have a negative effect upon habitat suitability, and can decrement a given index by as much 50%. A proposed approach is to develop a spatially explicit, interactive platform (likely a website) to allow for calculation of the spatial metrics and illustrate habitat development. Alberta Environment has already created the basic GIS layers that will be used as the base-mapping platform. This platform is then overlaid with additional GIS layers that represent projected ecosite development and associated HSIs, recalculated after accounting for spatial proximity.

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8 ACRONYMS

ACM	Alberta Climate Model
AET	Actual Evapotranspiration
AHMI	Annual Heat Moisture Index
AMI	Annual Moisture Index
AWHC	Average Water Holding Capacity
CRI	Climate Response Index
f	Function (describing the components of an equation)
ForWaDy	Forest Water Dynamics (a model)
GCM	Global Circulation Model
GDD	Growing Degree-Day
HS	Hybrid Simulation
HSI	Habitat Suitability Index
LAI	Leaf Area Index
m.a.s.l.	Metres Above Sea Level
MAT	Mean Annual Temperature
NEP	Net Ecosystem Productivity
NPP	Net Primary Productivity
OSRIN	Oil Sands Research and Information Network
P	Precipitation
PET	Potential Evapotranspiration
PWP	Permanent Wilting Point
SEE	School of Energy and the Environment
T	Temperature
TACA	Tree and Climate Assessment (a model)
TAP	Total Annual Precipitation

TDI	Transpiration Deficit Index
VR	Vegetative Reproduction

9 LIST OF OSRIN REPORTS

OSRIN reports are available on the University of Alberta's Education & Research Archive at https://era.library.ualberta.ca/public/view/community/uuid:81b7dcc7-78f7-4adf-a703-6688b82090f5. The Technical Report (TR) series documents results of OSRIN funded projects. The Staff Reports series represent work done by OSRIN staff.

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APPENDIX 1: Climate Change Models

Modifiers for monthly values for climate change scenarios downscaled for northern Alberta (Alberta Environment, unpublished data). Temperature modifiers are absolute changes in temperature (°C), while the precipitation modifier is a proportional change.

Model	Scenario	Period	Month	Modifiers		
				Min. Temp.	Max. Temp.	Precip.
CCSRNIES	A1F1	2020	1	-0.4	-0.4	0.96
			2	-0.4	-0.4	0.96
			3	1.5	1.5	0.95
			4	3.3	3.3	1.08
			5	2.6	2.6	1.18
			6	0.4	0.4	0.87
			7	0.7	0.7	0.92
			8	0.8	0.8	0.85
			9	0.0	0.0	1.08
			10	0.2	0.2	1.02
			11	0.8	0.8	1.03
			12	1.9	1.9	1.08
		2050	1	5.0	5.0	1.16
			2	4.1	4.1	1.16
			3	5.5	5.5	1.15
			4	7.5	7.5	1.22
			5	5.1	5.1	1.37
			6	2.7	2.7	0.93
			7	3.2	3.2	0.92
			8	3.0	3.0	0.85
			9	2.2	2.2	1.08
			10	3.7	3.7	1.09
			11	6.8	6.8	1.08
			12	9.8	9.8	1.28

Model	**Scenario**	**Period**	**Month**	**Modifiers**		
				Min. Temp.	Max. Temp.	Precip.
		2080	1	13.1	12.6	1.30
			2	14.0	14.1	1.35
			3	16.5	16.5	1.46
			4	14.6	15.6	1.61
			5	11.4	10.1	1.72
			6	6.1	6.1	1.07
			7	6.4	6.5	1.15
			8	6.9	7.1	0.91
			9	6.2	6.3	1.17
			10	8.0	8.0	1.37
			11	10.9	11.0	1.27
			12	15.6	15.3	1.59

Model	**Scenario**	**Period**	**Month**	**Modifiers**		
				Min. Temp.	Max. Temp.	Precip.
CGCM2	B23	2020	1	3.3	3.3	0.86
			2	1.8	1.8	0.86
			3	3.0	3.0	0.92
			4	1.1	1.1	0.92
			5	1.8	1.8	1.08
			6	1.1	1.1	1.15
			7	1.3	1.3	0.95
			8	1.6	1.6	0.93
			9	0.8	0.8	1.04
			10	1.0	1.0	1.13
			11	0.7	0.7	1.09
			12	2.3	2.3	1.01
		2050	1	4.3	4.3	0.95
			2	3.6	3.6	0.95
			3	3.6	3.6	0.97
			4	1.9	1.9	0.97
			5	3.2	3.2	1.05
			6	1.8	1.8	1.06
			7	1.9	1.9	0.90
			8	2.2	2.2	1.00
			9	1.6	1.6	0.94
			10	1.0	1.0	1.17
			11	0.8	0.8	1.03
			12	3.9	3.9	0.99
		2080	1	6.3	4.7	0.90
			2	4.4	4.5	0.85

Model	**Scenario**	**Period**	**Month**	**Modifiers**		
				Min. Temp.	Max. Temp.	Precip.
			3	4.2	4.1	0.89
			4	2.4	2.4	1.08
			5	3.3	3.4	1.19
			6	2.1	2.1	1.15
			7	2.8	2.7	1.01
			8	2.9	3.3	0.85
			9	1.9	2.2	0.91
			10	0.9	1.4	1.03
			11	0.5	1.0	0.97
			12	5.6	4.9	0.83

Model	**Scenario**	**Period**	**Month**	**Modifiers**		
				Min. Temp.	Max. Temp.	Precip.
HADCM3	A2A	2020	1	-1.6	-1.6	1.06
			2	1.6	1.6	1.06
			3	0.1	0.1	1.16
			4	0.2	0.2	1.10
			5	0.6	0.6	1.00
			6	1.0	1.0	1.16
			7	1.7	1.7	1.13
			8	1.5	1.5	1.07
			9	1.7	1.7	0.89
			10	1.0	1.0	1.13
			11	1.3	1.3	1.08
			12	0.4	0.4	1.10
		2050	1	-0.9	-0.9	1.11
			2	1.7	1.7	1.11
			3	0.5	0.5	1.16
			4	1.1	1.1	1.31
			5	2.4	2.4	0.96
			6	2.3	2.3	1.28
			7	3.6	3.6	1.15
			8	3.0	3.0	1.03
			9	3.0	3.0	0.89
			10	1.6	1.6	1.13
			11	2.2	2.2	1.12
			12	1.7	1.7	1.37
		2080	1	1.0	1.2	1.43
			2	2.9	2.7	1.24

Model	**Scenario**	**Period**	**Month**	**Modifiers**		
				Min. Temp.	Max. Temp.	Precip.
			3	1.5	1.0	1.36
			4	2.6	2.6	1.41
			5	4.0	4.7	0.77
			6	4.4	4.6	1.30
			7	5.2	5.4	1.15
			8	5.0	5.2	0.98
			9	4.9	5.6	0.82
			10	2.5	2.6	1.37
			11	4.0	3.8	1.17
			12	4.4	4.1	1.40

Model	**Scenario**	**Period**	**Month**	**Modifiers**		
				Min. Temp.	Max. Temp.	Precip.
HADCM3	B2B	2020	1	-1.2	-1.2	0.99
			2	1.5	1.5	1.16
			3	-0.1	-0.1	0.94
			4	1.0	1.0	1.11
			5	1.0	1.0	1.01
			6	1.5	1.5	1.23
			7	1.5	1.5	1.01
			8	1.6	1.6	1.08
			9	1.2	1.2	1.11
			10	0.2	0.2	1.07
			11	1.1	1.1	1.00
			12	2.0	2.0	1.14
		2050	1	1.6	1.6	1.15
			2	2.8	2.8	1.15
			3	1.5	1.5	1.13
			4	1.8	1.8	1.34
			5	1.4	1.4	1.02
			6	2.1	2.1	1.23
			7	2.6	2.6	0.99
			8	2.9	2.9	1.05
			9	2.5	2.5	1.22
			10	1.5	1.5	1.05
			11	3.3	3.3	1.09
			12	3.5	3.5	1.27
		2080	1	2.4	2.4	1.31
			2	3.2	3.1	1.29

Model	**Scenario**	**Period**	**Month**	**Modifiers**		
				Min. Temp.	Max. Temp.	Precip.
			3	1.7	1.6	1.21
			4	2.6	2.7	1.26
			5	2.0	2.1	0.95
			6	2.7	2.8	1.29
			7	3.7	3.8	1.00
			8	3.9	3.9	1.08
			9	2.9	3.0	1.31
			10	2.1	1.9	1.16
			11	4.5	4.1	1.23
			12	5.6	5.6	1.50

Model	**Scenario**	**Period**	**Month**	**Modifiers**		
				Min. Temp.	Max. Temp.	Precip.
NCARPCM	A1B	2020	1	2.5	2.5	0.97
			2	1.1	1.1	0.99
			3	0.4	0.4	1.09
			4	0.7	0.7	1.06
			5	1.1	1.1	1.02
			6	0.5	0.5	1.08
			7	0.3	0.3	0.89
			8	0.3	0.3	1.11
			9	0.3	0.3	1.18
			10	0.8	0.8	1.08
			11	2.0	2.0	1.13
			12	2.1	2.1	0.97
		2050	1	5.3	5.3	1.27
			2	2.7	2.7	1.08
			3	2.2	2.2	1.18
			4	2.0	2.0	1.14
			5	1.9	1.9	1.10
			6	1.2	1.2	1.01
			7	1.1	1.1	0.92
			8	1.6	1.6	1.11
			9	2.2	2.2	1.15
			10	1.9	1.9	1.19
			11	3.2	3.2	1.07
			12	4.0	4.0	1.22
		2080	1	5.9	5.2	1.30
			2	2.7	2.3	1.02

Model	**Scenario**	**Period**	**Month**	**Modifiers**		
				Min. Temp.	Max. Temp.	Precip.
			3	2.6	2.4	1.07
			4	2.9	2.6	1.31
			5	1.6	1.3	1.09
			6	1.3	1.8	0.93
			7	1.1	1.5	0.87
			8	1.5	1.6	1.04
			9	2.2	2.1	1.18
			10	2.4	2.3	1.23
			11	5.7	5.2	1.16
			12	6.4	6.0	0.95