Canadian Council of Forest Ministers

Conseil canadien des ministres des forêts

# Vulnerability of Canada's Tree Species to Climate Change

## and Management Options for Adaptation: An Overview for Policy Makers and Practitioners

# VULNERABILITY OF CANADA'S TREE SPECIES TO CLIMATE CHANGE AND MANAGEMENT OPTIONS FOR ADAPTATION:

## An Overview for Policy Makers and Practitioners

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**Library and Archives Canada Cataloguing in Publication**

Johnston, Mark H. (Mark Harvey), 1953-

Vulnerability of Canada's Tree Species to Climate Change and Management Options for Adaptation: An Overview for Policy Makers and Practitioners.

Issued also in French under title: Vulnérabilité des arbres du Canada aux changements climatiques et propositions de mesures visant leur adaptation : un aperçu destiné aux décideurs et aux intervenants du monde forestier.

Cover's lower photograph: Red Rock Nursery.
By Lorraine Maclauchlan.

Includes bibliographical references.

ISBN 978-1-100-13196-2
Cat. no.: Fo4-28/2009E (Print)

Available also on the Internet.

ISBN 978-1-100-13845-9
Cat. no.: Fo4-28/2009E-PDF (Electronic)

1. Forest management – Environmental aspects – Canada.
2. Trees – Varieties – Environmental aspects – Canada.
3. Forest biodiversity – Environmental aspects – Canada.
4. Climatic changes – Canada.
5. Forest policy – Canada.

I. Canadian Council of Forest Ministers

SD387 E85 J63 2009 634.9'20971 C2009-980299-6

Printed on Recycled paper

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## ACKNOWLEDGEMENTS

The authors acknowledge guidance from members of the CCFM Climate Change Task Force: Stan Kavalinas and Evelynne Wrangler (Alberta); Kathy Hopkins and Jim Snetsinger (British Columbia); Darcie Booth, Kelvin Hirsch, and Tim Sheldan (Canada); Jocelyn Baker (Manitoba); Mike Bartlett, (New Brunswick); Ivan Downton and Wayne Kelly (Newfoundland and Labrador); Tom Lakusta (Northwest Territories); Jorg Beyeler and Ed MacAulay (Nova Scotia); Dan McAskill (Prince Edward Island); Dwayne Dye (Saskatchewan); Shelley Webber (formerly of the Canadian Forest Service), numerous researchers and forest managers who were consulted about sources of vulnerability to Canadian tree species, and numerous individuals within jurisdictions who provided valuable technical content and feedback on this report. We also gratefully acknowledge the financial support provided by the jurisdictions.

# EXECUTIVE SUMMARY

## CONTEXT

Over the next several decades, the climate in Canadian forests will shift northward at a rate that will likely exceed the ability of individual tree species to migrate. While most tree species can migrate naturally up to a few hundred metres per year via seed dispersal, the climatic conditions in which each species thrives may move north by several thousand metres per year. Canada's forests are home to well over 100 species of trees, of which 93 are commercially important. Canada's tree species are vulnerable to climate change because trees are sensitive to climate, and there is now little doubt that significant climate change will continue over the next century. In fact, the effects of climate change on tree species are already occurring. For example, drought has caused significant mortality of aspen trees in the southern boreal forest of Alberta and Saskatchewan, and warmer winters have contributed to a mountain pine beetle epidemic that is expected to kill more than three-quarters of the pine volume in British Columbia by 2015. Although it is expected that the overall net effect of climate change on commercially important tree species in Canada will be negative, a changing climate may also increase tree growth in some areas.

Adaptation to climate change by modifying forest management policies and practices has the potential to reduce the vulnerability of tree species to climate change. However, before the process of adaptation can begin, it is necessary to understand how and where tree species are vulnerable, and to identify viable adaptation options.

The purpose of this report is to provide a systematic national assessment of:

- tree species vulnerability to climatic change,
- management implications and options, and
- knowledge gaps in our understanding of both species vulnerability and adaptation.

## GENERAL EFFECTS OF CLIMATE CHANGE ON TREE SPECIES

Climate change effects on tree species will be ongoing, cumulative, and interactive. For example, trees that are stressed by changes in site conditions (such as the development of moisture limitations) will be more susceptible to insects and diseases that become more active due to changing climatic conditions. The many interactions and feedbacks in the life cycle of a tree add to the complexity of climate change effects. Ultimately, a comprehensive, integrated, systems approach that accounts for the full range of factors and the interactions between them is needed to understand what makes tree species vulnerable to climate change and how best to help them adapt.

Climate change will create changes in microclimates, local site conditions, disturbances (e.g., fire, insects, disease, drought, extreme storms), phenology (i.e., the timing of biological activity over a year in relation to climate), and the distribution, abundance, and ecosystem interactions of invasive species, all of which could lead to increased tree mortality and changes in competitive interrelationships (including the potential for the introduction of exotics). Tree species and genotypes will acclimatize, adapt, and migrate; however, in many cases, the rate and magnitude of future climate change may significantly exceed the ability of tree species to naturally adjust. Tree species may, therefore, become increasingly maladapted (i.e., the local environment to which species are adapted begins to change at a rate beyond that which they can accommodate).

The general effects of climate change on tree species include changes in:

- regeneration success
- forest health (e.g., reduced vigour, maladaptation, and increased mortality)
- productivity (positive in some places; negative in other places)
- amount of growing stock (as a result of increased frequency, intensity, duration, and location of disturbances)
- species ranges, species composition, age class distribution, and forest structure at any given location, over time.

to the southern boreal forest are drying (including periodic intense droughts) and increased wildfire activity. Concerns have been expressed about the potential for the mountain pine beetle to spread into jack pine forests and move across the boreal forest into eastern Canada. However, experts are sceptical about this scenario because jack pine stands may not occur in sufficient density to allow mountain pine beetle populations to develop to the point of creating a widespread outbreak, even if climates warm enough to allow overwintering survival of the beetle. While northern and southwestern boreal forests are highly vulnerable to climate change, forests in the central and eastern portions of the boreal forest region are

## VULNERABILITY OF CANADIAN TREE SPECIES

Commercial tree species in all regions are threatened by climate change, but some are more vulnerable than others. The greatest warming will occur in the central and northern parts of Canada, an area dominated by boreal forest. Species in the northern boreal forest are highly adapted to cold climates. Increased wildfire activity, permafrost melting, and maladapted trees pose significant threats to northern species such as white and black spruce. Northern forests are also sparsely populated and have relatively low commercial timber value. Therefore, investment in human-assisted adaptation will likely be low. The main threats

less vulnerable because there is a lower likelihood of moisture deficits developing. However, there remains a need to incorporate climate change considerations into regeneration decisions across the boreal forest because of the potential for maladaptation and increased disturbance.

The Montane Cordilleran region of central British Columbia may experience a loss of alpine ecosystems as tree lines increase in elevation. Forest cover may decrease in dry areas of the southern interior of the region. Disturbance activity (i.e., fire, insects, drought, extreme weather) will increase throughout the Montane region, but there is the potential for productivity gains—at least up to 2050—in the northern portions of the region because moisture is not expected to be limiting. The southern montane forest is highly vulnerable whereas the northern montane forest is moderately vulnerable to climate change.

The Pacific Maritime, Mixedwood Plains, and Atlantic Maritime regions face an increased threat from biotic disturbance and extreme weather events (increased frequency and intensity of severe windstorms). However, the overall vulnerability of forests in these regions is expected to be lower than that of western boreal forests—at least up to 2050.

There will be areas of high vulnerability within local populations of tree species in all the regions mentioned above. For example, transition zones between regions and between ecosystems within those regions will be more vulnerable to climate changes because environmental controls within those zones are close to species' tolerance limits, and the capacity for genetic adaptation is lowest (particularly at the southern edge of species' ranges).

One of the more significant concerns about climate change is the uncertainty about what will actually happen. Although changes in the composition, structure, and age of forests will occur, there is uncertainty about the magnitude, location, and timing of those changes at local scales. Due to this lack of predictability, forest managers will have to deal with completely unanticipated and novel events. Moreover, the lessons learned about forest ecosystem function, succession, regeneration, disturbance processes, and growth based on historical observation and plot measurements may not help forest managers to predict what will happen in the future and design and implement effective management responses.

## A NEW APPROACH: REDUCING VULNERABILITY THROUGH ADAPTATION

Climate change has important implications for the management of forest tree species in Canada. The vulnerability of commercially important tree species in Canada could be reduced by applying early adaptation measures. Early adaptation offers the potential to both minimize negative impacts and maximize benefits associated with climate change (e.g., timber management policies and controls could be modified to take advantage of any productivity gains). Several actions will facilitate adaptation, including:

- considering climate change during activities such as planning, reforestation, stand tending, and harvesting (i.e., mainstreaming climate change into forest management using a systems approach)
- developing capacity for ecological and genecological modelling to address questions related to shifts in species distributions, assisted migration of species and seedlots, and diversification of species and seed sources in reforestation
- reducing vulnerability to climate change by developing, sharing, and adopting climate-sensitive best management practices
- reducing the risk of losses to catastrophic disturbance through harvesting and "climate conscious" management (e.g., managing forest structures to reduce the risk of large fires or pest outbreaks)
- enhancing species-level monitoring (e.g., growth, mortality, dieback) to ensure the early detection of climate change impacts and effectiveness of adaptation measures
- incorporating vulnerability analysis, risk analysis, and adaptive management into forest management practices that are related to reforestation and species composition choices

- continually identifying key knowledge gaps, institutional arrangements, and policies that pose significant barriers to adaptation, and taking actions to rapidly address them

## OPTIONS AND OPPORTUNITIES

Adaptation efforts that could reduce tree species vulnerability include:

- ensuring that the next generation of trees is better suited to the climatic environments within which they will be growing (i.e., facilitating migration, managing gene pools, and taking account of the potential range of future conditions when selecting species for stand regeneration)
- minimizing losses to the current inventory from climate change-induced disturbances
- modifying management of the current generation of trees such that the risks of maladaptation of some species are taken into account
- adopting climate-sensitive sustainable forest management best practices and implementing no-regret options (i.e., actions that are beneficial today and very likely to be beneficial in the future regardless of what form climate change takes)

Potential options for tree species management include:

- developing climate-based seed selection systems for reforestation
- accounting for changes in future site conditions in management decisions (e.g., anticipating where moisture may become limiting)
- examining the potential for establishing genetic outposts (small plantations of seed sources that are adapted to predicted future climates in remote locations) to hasten the adaptation of forests in unmanaged areas
- implementing long-term, multi-species provenance field trials to assess the climatic tolerance of seed sources in order to optimize assisted migration strategies. In these trials, researchers could include seed sources from the northern United States because they may be the best adapted to future Canadian climates, and they could include test sites in northern U.S. locations that have climates similar to those that will soon occur in Canada.
- examining opportunities to increase genetic and species diversity when planting forests as a means of increasing capacity to buffer climate uncertainty
- using large scale disturbances as windows of opportunity to re-establish forests that are less vulnerable to future climate change
- ensuring all disturbed or harvested forests are promptly reforested with species and seed sources that are adapted to predicted future climates (i.e., using assisted migration)
- reducing reliance on natural regeneration where naturally regenerated forests will be significantly maladapted to future climates
- increasing experimental plantings to test options for new species, and reviewing existing plantations of exotics across provinces and ecozones

- managing species for shorter rotations
- selecting and breeding to enhance traits that may be more suited to changed environmental conditions
- planting drought-resistant species in areas that are prone to increased drought
- re-evaluating seed orchard locations relative to potential future climate change
- identifying stands and forest structures that are susceptible to large scale disturbances, and using forest management to favour species and structures that are less vulnerable

An important caveat is that specific actions in specific regions will need to be implemented with care and caution. For example, adaptations pertaining to regeneration will need to take account of both the current and future climate. In some cases, knowledge gaps will need to be addressed before codes and standards for widespread implementation of adaptations are possible. In the interim, experimental testing, trials, and monitoring of new approaches may be needed. Also, greater flexibility in institutions to allow for local adaptation may be called for. What works in one location may not work in another. Diversified prescription portfolios, flexible codes and standards, and local adaptive management approaches will enhance the capacity of forest managers to adapt to climate change.

## NEXT STEPS: MOVING BEYOND TREES TO FORESTS AND THE FOREST SECTOR

This report focuses on climate change and the vulnerability of commercially important tree species in Canada. This is a vitally important first step; however, the Canadian Council of Forest Ministers (CCFM) acknowledges that this provides only a partial picture. As has been implied in this study, and as is reflected in the current CCFM document *A Vision for Canada's Forests: 2008 and Beyond*, the impacts of climate change go beyond impacts on tree species. Climate change will also affect forest landscapes, the forest sector, the full array of forest management objectives that are part of sustainable forest management, and an array of constituencies (forest industry, forest-based communities, protected areas, First Nations populations, wildlife, water, public health and safety, timber supply, etc.). Therefore, a comprehensive approach that considers climate change in a broader context will be needed. It is the intention of the CCFM to follow up on this study with an assessment that focuses on these broader issues. This will include an evaluation of climate change impacts at a broader landscape scale and an assessment of how these changes will impact forest assets and values. Phase 2 will develop a better understanding of climate change vulnerabilities foreseeable for sustainable management of Canada's forests at the national level. It will also identify potential approaches to adaptation to reduce these vulnerabilities. A goal of the next phase is to develop a framework and guidance documents to assist jurisdictions and forest practitioners to incorporate climate change considerations into Sustainable Forest Management in Canada. This next phase will build upon earlier ecological and socio-economic assessments of the Canadian Council of Forest Ministers.

# INTRODUCTION

Canada is a forest nation and is committed to the principle of sustainable forest management. This means that Canada is committed to maintaining forests and ecological processes in order to ensure that the socio-economic and environmental benefits that are provided by forests will be available in the present and the future. However, Canada's forest managers now face a new challenge: dealing with and preparing for the impacts of climate change on forested ecosystems. It is an influence that could have profound impacts on tree species and forests, particularly if corrective actions to reduce greenhouse gas emissions are not taken relatively soon.

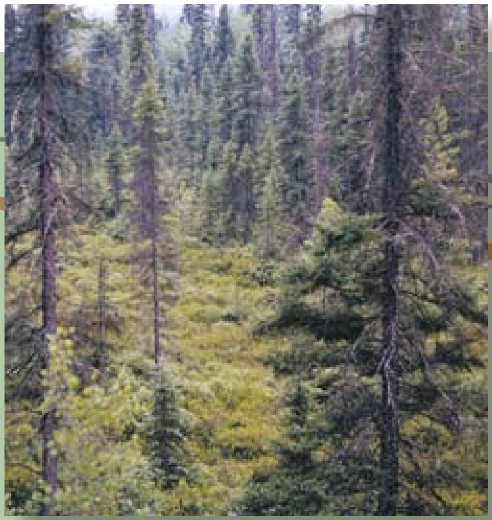
Canada's forests are home to well over 100 species of trees, of which 93 are considered to have commercial value by the members of the Canadian Council of Forest Ministers (CCFM) (Appendix 1). Canada's tree species are vulnerable to climate change because trees are sensitive to climate, and there is now little doubt that significant climate change will continue over the next century. In fact, the effects of climate change on tree species are already occurring. For example, drought has caused significant mortality of aspen in the southern boreal forest, and warmer winters have contributed to a mountain pine beetle epidemic, which is expected to kill more than three-quarters of the pine volume in British Columbia by 2015. Although it is expected that the overall net effect of climate change on commercially important tree species in Canada will be negative, it is important to note that a changing climate may also lead to increased tree growth in some species in some areas.

Adaptation to climate change by modifying forest management policies and practices can potentially reduce the vulnerability of some tree species to climate change. However, the first step in adaptation will be to determine how tree species are vulnerable to climate change, and to identify areas where forests and trees will be exposed to these vulnerabilities, because that is where adaptation requirements will be the greatest.

The purpose of this report is to provide a systematic national assessment of:

- tree species vulnerability to climatic change,
- management implications and options, and
- knowledge gaps related to our understanding of both species vulnerability and adaptation.

This report is aimed at forest managers and policy-makers who will be faced with making decisions in an era of a changing environment and increasing uncertainty. This is not a detailed technical report but rather an attempt to highlight the most important issues related to tree species vulnerability and to identify potential management actions that will assist decision-makers in adapting to the impacts of climate change.



## CURRENT DISTRIBUTION OF TREE SPECIES IN CANADA[1]

Canada is host to a wide variety of tree species. Past climate is an important determinant of the present-day distribution of tree species in Canada. The remainder of this section provides an overview of the major forest ecozones in Canada (Figure 1), the typical climate of these ecozones, and the major tree species that are present in each.

The **Taiga Plains** ecozone is Canada's northernmost forested ecozone. Short, cool summers and long, cold winters result from the influence of arctic air for most of the year. This ecozone is a transition between mixed forest–tundra and dense coniferous forest. The predominant tree species is black spruce, which generally occurs as an open, slow-growing species. Along nutrient-rich alluvial flats of the larger rivers, white spruce and balsam poplar grow as large as those in the boreal forest.

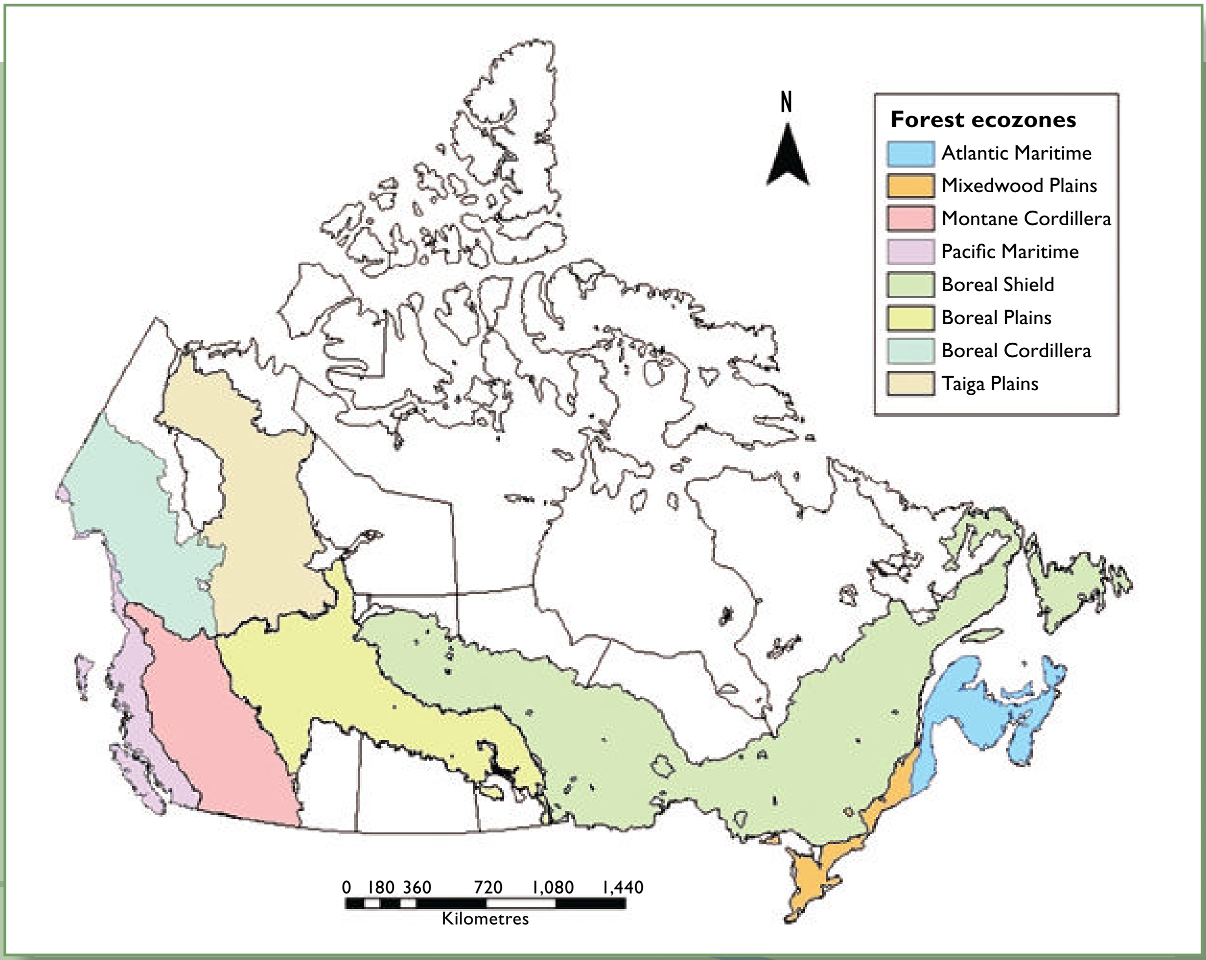
The **Boreal Cordillera** ecozone, covering sections of northern British Columbia and the southern Yukon, has a Pacific Maritime influence that moderates temperatures over most of its area. The climate is marked by long, cold winters and short, warm summers. The ecozone is 51% forested with cover ranging from closed- to open-canopy forest. Tree species include white and black spruces, alpine fir, lodgepole pine, trembling aspen, balsam poplar, and white birch. Shrub birch–willow communities are common in the subalpine forest and extend into the alpine tundra above the tree line.

[1] Adapted from CCFM. 2006. Criteria and Indicators of Sustainable Forest Management in Canada. Canadian Council of Forest Ministers, Ottawa, Ont. http://www.ccmf.org/english/coreproducts-criteria_in.asp, accessed July 20, 2009

The **Boreal Plains** ecozone extends from British Columbia in the northwest to the southeastern corner of Manitoba. Cold winters and moderately warm summers are characteristic of the strongly continental climate. Jack and lodgepole pines, white and black spruces, balsam fir, and tamarack are the main coniferous species, and mixed stands of aspen and white spruce occur on nutrient-rich sites.

The **Boreal Shield** ecozone stretches from the eastern tip of Newfoundland to the northeastern corner of Alberta. It is the largest ecozone in Canada, encompassing almost 20% of the country's land area. The ecozone has a strongly continental climate characterized by long, cold winters and short, warm summers except in the eastern coastal margins where it is moderated by maritime conditions. Vegetation in the Boreal Shield is the result of cool temperatures, a short growing season, frequent forest fires, and acidic soils. The ecozone is approximately 75% forested with much of it still in wilderness condition. Closed stands of conifers, largely white and black spruce, balsam fir, and tamarack, are characteristic. Toward the south, there is a wider distribution of broadleaf trees, such as white birch, trembling aspen, and balsam poplar, and needle-leaved trees, including spruces, pines (eastern white, red, and jack), and balsam fir. Fire suppression and harvesting have resulted in an increase in the balsam fir content of stands, usually at the expense of white spruce. In the eastern portion of the ecozone, balsam fir is often the dominant species. On lowland sites, black spruce occurs in nearly pure stands.

**FIGURE 1. Map of forested ecozones across Canada.**



The **Pacific Maritime** ecozone forms a narrow zone along the Pacific coast, and approximately 50% of the area is forested. This ecozone has some of the most productive climatic conditions in Canada (mild, wet winters and relatively cool, dry summers). The ecozone is characterized by several commercially important coniferous evergreen species not found in other regions of Canada, including Douglas-fir, western redcedar, western hemlock, and Sitka spruce. Natural stands can reach impressive ages and volumes due to long intervals between disturbances such as fire or windstorms.

The **Montane Cordillera** ecozone, nestled between the Pacific Maritime, Boreal Plains, and Boreal Cordillera, is the most complex of all the ecozones, with an exceptional diversity of topography and climate. Several mountain ranges run north to south and are separated by several interior plains. This ecozone is also home to Canada's only true desert. Depending on elevation and exposure, vegetation varies from alpine tundra to high-elevation subalpine fir and Engelmann spruce, to dense conifer forest that is almost coastal in appearance, to dry sagebrush and grasslands. Approximately 73% of the area is forest. The Montane Cordillera is a fire-dominated ecosystem. Fire suppression has resulted in the development of older age class forests, which are becoming increasingly prone to catastrophic wildfire. Following long periods of aggressive fire suppression, insects associated with mature forests, such as bark beetles, are also able to cause major damage to the forest.

The **Mixedwood Plains** ecozone covers the Great Lakes–St. Lawrence River valley. The ecozone is the northernmost extension of the deciduous forest biome that extends throughout much of the eastern United States. The climate is marked by hot, humid summers and cool winters. Once heavily forested, the Mixedwood Plains supported a greater diversity of trees and plants than any other part of Canada. It now has just over 20% forest cover, ranging from mixed deciduous–coniferous stands in the northern portions to highly diverse deciduous stands of the Carolinian forest in the southwest near Windsor, Ontario. Examples of tree species include the tulip tree, Ohio buckeye, bitternut hickory, black walnut, sycamore, and blue ash. Most of the deciduous forest has been cleared for farms, orchards, highways, and cities.

The **Atlantic Maritime** ecozone covers all of Nova Scotia, New Brunswick, Prince Edward Island, and part of Québec. The Atlantic Ocean creates a cool, moist maritime climate. The ecozone is heavily forested with mixed stands of conifers (notably balsam fir) and deciduous species (such as maple and birch). It contains elements of the Acadian, the Great Lakes–St. Lawrence, and boreal forest regions. Examples of tree species in this region include red, black, and white spruce, balsam fir, sugar maple, yellow birch, and beech. This ecozone has the highest percentage of private woodlots in Canada, as well as one of the longest histories of tree harvesting and land clearing.

# HOW CLIMATE CHANGE AFFECTS TREE SPECIES

Species, and genotypes within species, are typically adapted to their native climatic environments. As shown in the previous section, environmental and climatic niches for tree species vary widely across the Canadian landscape. As a result, Canada is host to a diverse array of tree species and species associations. However, environmental variation within ecozones, coupled with random genetic mutation, give rise to thousands of genotypes within species that are widely dispersed.

Climate change will have many widely varying effects on trees and tree species composition within forest ecosystems (Figure 2). Many of these effects will occur simultaneously, leading to cumulative effects. For example, changes in climate at any particular location may simultaneously affect site conditions, exposure to disturbance, and physiological functioning of individual organisms. Also, climate change effects on individual tree species may result from responses to several interacting stressors. For example, trees affected by moisture stress are typically more susceptible to insects that become more active in a warmer climate. The many interactions and feedbacks associated with climate change are complex and difficult to predict. It is possible, however, to identify drivers of change for trees and forests, interactions among these drivers, and some of the overriding factors that will ultimately determine the magnitude of the impacts on tree species. Figure 2 shows a number of interacting pathways through which climate change can affect trees species and forest ecosystems. Some of the specific elements are discussed below. However, it is important to keep in mind the complexity of forest ecosystems and the strong interrelationships that exist between individual species or organisms, their local environment (including both site conditions and climate), and other plant and animal species. A systems approach that accounts for the full range of drivers of change and the interactions among them is needed to fully understand tree species vulnerability to climate change.

The remainder of this section considers direct and indirect impacts of climate change on tree species. Impacts can be broadly divided into two categories: maladaptation and disturbance. Maladaptation occurs when the local environment to which species are adapted begins to change at a rate that is beyond the species ability to accommodate. Since trees are long-lived organisms and individuals are unable to migrate, the current population of trees will likely become increasingly maladapted as climate change occurs. However, succeeding generations may be able to migrate or adapt, either naturally or through human intervention. These possibilities are discussed below. Disturbance, the second category of climate change impacts, includes both abiotic factors (e.g., fires, windthrow) and biotic factors (insects, disease, parasites). It is important to understand that these categories are distinct yet interrelated. For example, trees that are maladapted due to increasing water stress are more susceptible to attack by defoliating insects.

**FIGURE 2. A map of climate change impacts on forests.** (Source: Williamson et al. 2009 – reprinted with permission)

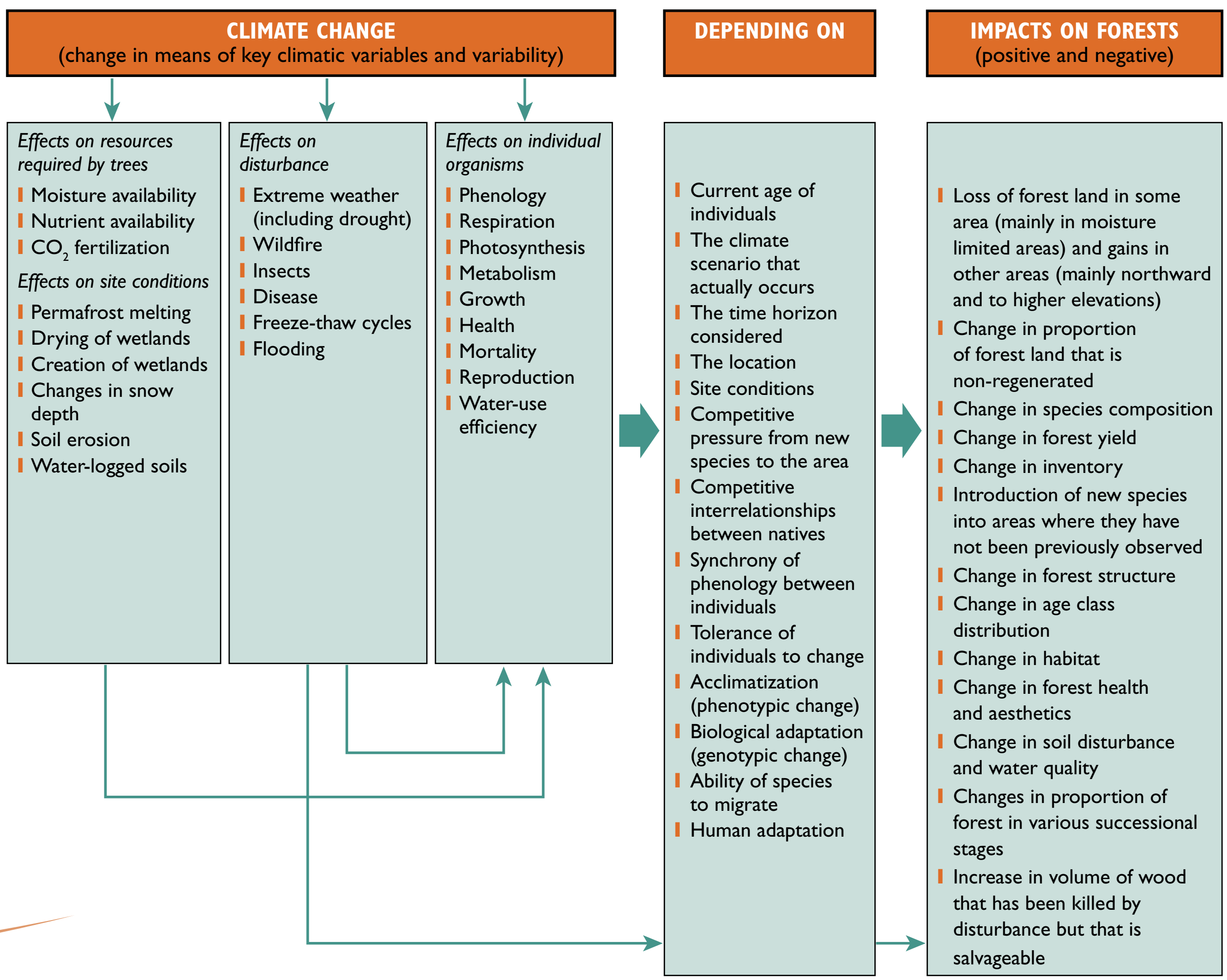
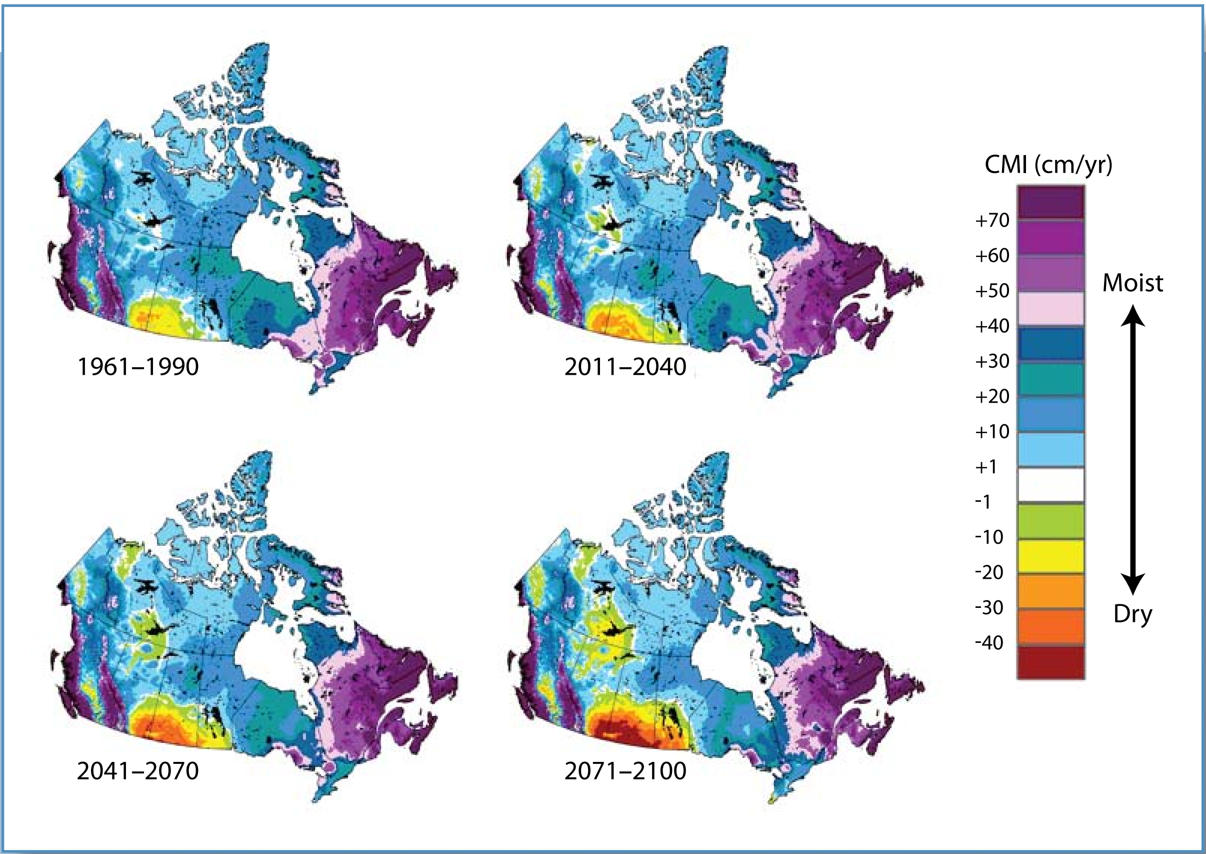


**FIGURE 3. Expected change in climate moisture index (CMI) across Canada over time for one climate scenario.** (reprinted with permission from Lemprière et al. 2008)




## Maladaptation

### SITE FACTORS

Climate change will have direct effects on microclimates. In general, warming implies there will be longer growing seasons, warmer growing season temperatures, decreases in diurnal temperature variation, warmer winters, and changes in the amount, frequency, and distribution of precipitation and in the proportion that falls as rain or snow. These changes will vary across the country and will intensify over time as the climate continues to warm.

Soil moisture that is available to trees will increase in some areas and decrease in others (Figure 3), and will vary seasonally. Soil nutrients may change due to changes in rates of decomposition and mineralization. Large areas of the northern forest will be affected by permafrost melting, which could result in significant negative impacts on forest cover in the near future (but the possibility of increased productivity in the long term). Some areas may become wetter; others may become drier.

Soil available water-holding capacity (AWC) is a critical factor in determining water availability for uptake by plants. Work in Saskatchewan indicates that differences in AWC generated by a warmer, drier future climate could strongly affect forest biomass production. Productivity on sites with low AWC (less than 100 mm storage) will likely decline under future climate scenarios. On sites with moderate AWC (100–200 mm storage), productivity is projected to increase initially in response to warmer temperatures but decrease in later decades. However, on sites with high AWC (greater than 200 mm storage), forest productivity will continue to increase during the 21st century because soil water storage will be sufficient to support increased growth.

## SYNCHRONY OF PHENOLOGY

Climate change will have numerous subtle but important effects on tree species. Phenology is the study of the timing of biological activity over the course of a year, particularly in relation to climate. For trees, climate affects such things as the timing of flowering, bud set, bud burst, growing season length, dormancy period, and availability of pollinators, etc. A number of phenology-related effects of recent climate change are already being observed. For example, bud burst in sugar maple and the flowering of aspen are occurring earlier in the year. In general, the review of climate records from the last 100 years or more shows that growing seasons have lengthened significantly throughout Canada. Remote sensing studies of boreal forests have shown that the growing season has increased in both North America and northern Eurasia.

Interspecies phenological synchrony is important to ecosystem function. Warmer temperatures will potentially cause asynchrony. For example, the emergence of spruce budworm is timed to occur at approximately the same time that buds flush on host trees. Late spring frosts can kill the new buds and deprive the emerging insects of food. Alternatively, earlier bud flush in some areas may facilitate spruce budworm outbreaks. Thus, climate change has the potential to change species phenology and disrupt ecological interactions, which can result in more unstable and unpredictable ecosystems.

## PHYSIOLOGICAL RESPONSE OF TREES

A key measure of plant growth is net primary productivity (NPP), which is an expression of the amount of biomass added to the plant as a result of photosynthesis. NPP is expressed as units of biomass (or carbon) produced per unit ground area per unit of time (e.g., grams per $m^2$ per year). Plant productivity responses to increasing temperature are complex and vary with species, tree age, needle leaf versus broadleaf foliage, and stresses imposed by water and nutrient deficiencies, pests, diseases, and parasites. However, most plant physiological processes, including photosynthesis, have optimal temperature ranges, above which they begin to decline. Hence, a longer growing season can have positive or negative effects on NPP over a year. For example, where water and nutrients are not limiting and growing season temperatures are presently below a plant's optimum temperature range, climate warming will have a positive effect on annual NPP. However, if climate warming causes increased annual respiration relative to annual photosynthesis, then a longer growing season will result in a decline in NPP.

The potential for moisture deficits will be an important factor in determining climate change impacts on tree species. Much of central and western Canada is expected to experience significant temperature increases with little change in precipitation. Higher average temperatures will result in increased evapotranspiration and an increased occurrence of soil water shortages (i.e., droughts). These conditions will be exacerbated on sites with coarse-textured soils and low AWC. Some tree species are capable of extending roots deeper in search of water during drought. As moisture becomes increasingly limited, trees employ two strategies to cope with water stress. In dehydration postponement, trees shed some or all of their leaves, which reduces transpiration and postpones dehydration. In dehydration tolerance, trees come to equilibrium with the drought by dehydrating—i.e., the cells shrink and chemical changes reduce the amount of water taken up by the cells. Tree species vary in their ability to tolerate moisture deficits. For example, black spruce can tolerate dehydration, whereas jack pine can postpone dehydration. If moisture deficits become prolonged relative to the conditions to which trees are adapted, all tree species could eventually be susceptible to drought impacts.

Increased atmospheric $CO_2$ concentration affects a number of physiological factors. Trees take up $CO_2$ through stomata in the leaves but lose water at the same time through transpiration. Photosynthesis is enhanced under higher levels of atmospheric $CO_2$. This is known as the $CO_2$ fertilization effect. Trees may show increased growth due to $CO_2$ fertilization, particularly if other resources (e.g., water, nutrients) are not limiting. However, the net benefits of $CO_2$ fertilization to tree and forest productivity are presently unclear. Much of the recent research indicates that increased growth lasts only a few years and is highly variable among species. In addition, with increased atmospheric $CO_2$, less water is transpired per unit of $CO_2$ uptake (this ratio is known as water-use efficiency or WUE). Future drought scenarios suggest that increased WUE resulting from higher $CO_2$ levels could be particularly important on water-limited sites, such that tree growth might continue where it would otherwise be critically limited. However, it is still unclear how much impact this process will have in cases where other environmental factors are cumulatively affecting survival and growth.

## REGENERATION

Climate change will affect regeneration success of commercially important tree species in several ways. Trees are generally considered to be most vulnerable to climatic stresses during the regeneration phase. Climate change will affect flowering, pollination, seed formation, germination, and seedling survival. Regeneration success will, therefore, depend on the future capacity of trees to produce viable seed and on the capacity of those seeds to germinate. Established seedlings must also be able to survive and grow productively in climatic conditions that may differ significantly from those experienced by the parent trees. Climate change will alter competitive relationships among native plants at particular sites and may result in increased vigour of native plants and animals that compete with (e.g., grasses and shrubs) or feed on (e.g., rabbits and deer) tree seedlings. Native tree species may also have to compete with new exotic species that are better adapted to new climatic conditions. All of the above factors may have implications for regeneration planning, practices, and policy.

## MIGRATION

As the climate continues to change, tree populations will become progressively less well adapted to their environment. In order to survive, they will either have to adapt in place or migrate to more suitable locations. In general, tree species cannot rapidly invade new areas because of the time required for trees to grow to seed-bearing age and then produce and disperse seed. In addition, most tree species are not very efficient at seed dispersal—the average distance of seed movement is a few hundred metres per year. To keep up with the expected rate of climate change, seeds would need to move several thousand metres per year. Other constraints on migration could include the lack of suitable soil conditions, particularly north of present-day treelines, and landscape fragmentation in developed areas due to agricultural and urban development. Studies of post-glacial migration have shown that species move on the landscape as individuals and that currently observed species associations are the coincidence of several species occurring together spatially at this point in history. As species migrate and redistribute themselves, novel combinations of tree species and associated communities of pests and diseases are likely to emerge, which may make tree survival in new locations difficult. Finally, trees will have to compete with current residents of the new habitat, which will make establishment difficult in many cases.

Recent work by the Canadian Forest Service has provided an approach for determining the vulnerability of tree species to climate change based on aspects of tree genetics[2]. Species are characterized by their ability to adapt in place, their ability to migrate, and their phenotypic plasticity (the ability of existing individuals to tolerate changes in environmental conditions). Each of these factors can be ranked and combined to provide an index for individual species. The index ranges from 0 (low vulnerability) to 1 (high vulnerability). Recent application of this index indicates that a species such as aspen ranks low in vulnerability from a genetics perspective. This is due to its high genetic variability and its ability to resprout from the root system and broadcast seed over long distances. In contrast, red spruce ranks as highly vulnerable due to its low genetic variability and relatively poor ability to disperse seed. The index can be calculated for many commercial tree species by using existing data, and it will allow forest managers to start developing an understanding of species-level vulnerability.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## MODELLING OF SPECIES RANGE SHIFTS

The general picture of species distribution change that emerges from modelling is surprisingly consistent, although it is possibly biased by our collective intuition of what is likely to occur. Some aspects are clear: even if the projected warming conforms to "conservative" global climate model predictions, present-day climate zones will shift northward up to 5000 metres per year, whereas most tree species are unlikely to disperse seed farther than 100–200 metres per year. Although rare, long distance seed dispersal events can occur, but they will not drive natural, large-scale colonization of new regions fast enough to significantly compensate for projected species loss in existing forests.

Across Canada, expected trends in species ranges due to climate change can be summarized as follows:

**Northern boreal treeline:** Simulations for the northern boreal zone of Alaska suggest that where soil conditions are suitable, colonization by forest species along the broad front of tundra ecosystems could occur within 150–250 years, following a transitional treed-grassland phase similar to the current aspen parkland in the Prairie region. Field studies in Québec suggest that in regions where soils are skeletal or non-existent, colonization beyond the arctic treeline could take much longer.

**British Columbia:** The rich diversity of climate zones caused by mountainous topography and Pacific maritime systems has led to much greater genetic diversity in tree species in British Columbia than in other regions of Canada. Geographically defined seed planning units have been identified and used to guide regeneration efforts, which has enhanced the understanding of how present-day seed sources might contribute to natural and managed adaptation to a warmer climate. There is likely to be a decline in spruce-dominated forests in the central and southern interior of British Columbia, and beyond 2050, serious declines are predicted in the south and at lower elevations, with potential extirpations of some populations. Similarly, losses of sites suitable for interior Douglas-fir are likely in the south beyond 2080. However, suitable climate zones will expand into the north and east.

**Western boreal:** According to most climate model projections, this region will undergo the greatest warming, and the relatively low annual precipitation is unlikely to increase sufficiently to compensate for the consequent increase in summer evaporative demand. In the north, warming will lead to the expansion of zones that are suitable for pine species over the short term, but by 2050, total areas suitable for pines will likely be less than present day. In the southern forest-grassland transition zone, warming and drying are likely to result in progressive stages of dieback, with losses accelerated by fires and insect attacks. The earliest consequences of climate warming are likely to occur in Alberta and western Saskatchewan. Drought-prone spruce will be lost first, followed by pines and then aspen, to be replaced by some form of prairie grassland.

**Eastern boreal:** East of Lake Winnipeg, the influence of the Great Lakes and Atlantic storm systems increases annual precipitation compared to the western boreal; consequently, serious, widespread droughts in forested regions are unlikely even under a warmer climate regime. This suggests that in the eastern boreal zone, there is likely to be an increase in productivity and relatively little species loss, although spruces and birch may be out-competed by pine and aspen on drier sites. However, one study projects major losses of area suitable for black spruce and jack pine in central Ontario, with potential replacement in the longer term by hardwood species from the south.

**Southern Ontario, Québec, and the Maritimes:** Species diversity in this region is high, and models project that by 2100, northward shifts of 250–600 km will occur in climate zones that are suitable for many hardwood species. Some of these species presently occur naturally only south of the U.S. border. One study suggests that present-day sugar maple stands are at serious risk of decline, but another indicates the core range would be preserved under most climate model scenarios. The climate zone that is suitable for yellow birch is likely to shift from its present range in southern Québec and New Brunswick northeastward into central Québec. Balsam fir is likely to disappear from Nova Scotia and most of New Brunswick, and shift north into northeastern Québec and Labrador.

### SPECIES ADAPTATION

The ability of any tree species to adapt depends primarily on the availability of a genetically diverse population. Since most Canadian tree species are abundant, considerable genetic diversity undoubtedly exists, but it is largely unquantified. Rapid adaptation requires high genetic variation in traits of adaptive importance and populations that are large enough to sustain high selection pressures. Adaptation in a particular trait may occur rapidly in a population with high phenotypic variation, high heritability, large number of individuals, and strong selection pressure.

Species that have high fecundity, long distance pollen flow, and short generation times are likely to be more successful in adapting to a changing climate. These characteristics are often associated with pioneer species. Given that in many regions of Canada, higher levels of disturbance are expected to be associated with a changing climate, pioneer species may thrive and increase their relative abundance due to their ability to rapidly occupy disturbed sites.

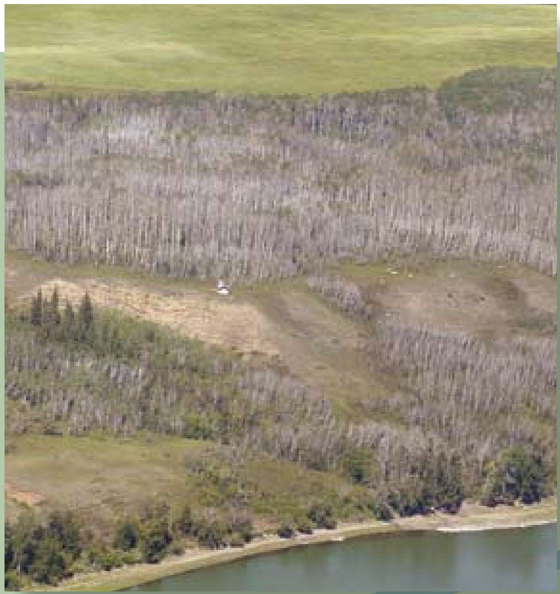
Phenotypic plasticity is the production of multiple phenotypes from one genotype in response to environmental conditions. It is an important characteristic of tree species because of the longevity of individual trees. Trees survive extreme climatic events with a variety of strategies due to phenotypic plasticity. The current level of phenotypic plasticity largely determines the longevity of current population survival under changing conditions. Migration and adaptation require time; phenotypic plasticity increases the time available for survival of a population's genes through adaptation or migration. Phenotypic plasticity varies considerably among species, and managers will be challenged with understanding how this factor can help in identifying suitable populations and species for future reforestation.

## Disturbance

### ABIOTIC DISTURBANCE

Climate change will produce increased frequency, duration, and intensity of disturbances (such as wildfire), and greater extremes in climate and weather events (e.g., intense precipitation, drought, windstorms, ice storms, and lightning).

Generally, trees have the ability to make short-tem adjustments in physiological processes to cope with variations in weather conditions. For example, species such as jack pine are able to withstand low soil water content for relatively long periods. However, if these events last too long, become too frequent, or increase in intensity, an individual tree's ability to tolerate them will be exceeded and mortality will result. In addition, some species are better adapted to periodic disturbance events than are others. An increase in the frequency of extreme events will tend to favour



early successional species (e.g., lodgepole pine). Over time, these species may become more dominant on the landscape. However, if such disturbances become very frequent, even well-adapted species are unlikely to reach seed-bearing age, at which point trees may disappear from the landscape entirely.

Fire is one of the most important agents that affect the structure and function of Canada's forests. On average, it affects over 2 million hectares of forest per year. Landscape-scale effects of climate change and fire will be addressed in the next phase of the CCFM project. Here we discuss species-level effects and how they may be affected by climate change.

Tree species' responses to fire can be characterized by their ability to either survive fire or regenerate following fire. Species can be classed as invaders, evaders, avoiders, resisters, or endurers, which facilitates the examination of presumed adaptive traits such as seeding from a distance, seed storage in soil seed banks, sprouting from protected tissues, and resistance to burning. Characteristics of these species types include the following:

Invaders have wind dispersed seeds and rapidly invade recently burned areas (e.g., trembling aspen, white birch). They are associated with short, intermediate, or long fire cycles.

Evaders store seed in the canopy (e.g., jack and lodgepole pine, black spruce) or the soil (pin cherry), thereby evading the high temperatures of fire near the ground. These species are associated with intermediate fire cycles.

Avoiders are very susceptible to mortality from fire and tend to occur late in the successional sequence (e.g., balsam fir, white spruce). They are associated with very long fire cycles.

Resisters become more tolerant of fire as they age. They have thick bark and undergo rapid self-thinning, which reduces ladder fuels and therefore the risk of crown fires (e.g., jack and lodgepole pine). These species are associated with intermediate fire cycles.

Endurers re-sprout following fire (e.g., trembling aspen, white birch in some circumstances). They are associated with short fire cycles.

This characterization can be applied to any species of interest as a means of predicting (in a general way) the effects of future fire regimes on species composition. For example, climate change projections suggest that western Canada will experience a doubling to tripling of area burned and more frequent and severe fire events in the latter half of this century. Under this scenario, it is likely that aspen (both an Endurer and Invader) will increase in abundance on the landscape, and the occurrence of white spruce (an Avoider) will decrease. In contrast, other work suggests that fires will become less frequent in some parts of eastern Canada, thereby favouring long fire cycle species such as balsam fir and white spruce (both Avoiders).

One of the most significant abiotic disturbances in maritime regions is extreme weather. Although there is significant uncertainty and ongoing debate, it has been suggested that future climate change will result in an increase in the frequency and intensity of tropical storms, which could cause more frequent severe storms in the Atlantic Maritime regions (e.g., Hurricane Juan, which caused major damage in September 2003). Shallow rooted species (e.g., spruces) could be particularly susceptible to increased windthrow. A higher frequency of intense rain events and greater impacts on riparian zones is anticipated. Storm surges and higher sea levels may affect coastal forests as well.

## INSECTS AND PATHOGENS

Many insects and pathogens attack trees, and many are specific to individual species or groups of species. Important insect pests in Canadian forests include the mountain pine beetle, forest tent caterpillar, and spruce budworm. Similarly, tree diseases are widespread and include fungal and bacterial pathogens, nematodes, and parasitic plants. In general, the projected changes in climate will promote pest and pathogen activity due to higher temperatures and reduced winter mortality. However, the complex interactions among pathogens, hosts, and environmental conditions make specific predictions difficult. A warmer and drier climate may encourage some pathogens but discourage others.

### Insects

Climate change will affect insect pests both directly and indirectly. Insect survival and development are directly affected by temperature. In Canadian forests, increases in summer temperatures will generally accelerate insect development rates. Some insects may shift from completing a generation every two years (semivoltism) to completing one generation per year (univoltism), a factor that contributes to large-scale outbreaks. A warmer climate could also lead to more successful overwinter survival. Outbreaks may also increase toward the northern limits of host species due to warming temperatures relative to their current distribution.

The indirect effects of climate change on insects are more complex; therefore, they are more difficult to predict. Because trees are likely to become increasingly maladapted to their environment, particularly in the early decades of climate change, they are more likely to be attacked by insects.

Climate change will affect the developmental sequence of insects and their predators. For example, natural insect enemies of defoliator species depend on climatic factors to maintain their life processes and synchronicity with their insect hosts and the forest habitat in which they live. Key parasitoid and predatory species can cause high mortality of late larval stage defoliators, and can be a primary driver in causing the collapse of outbreaks. However, predicting the effects of climate change in these types of relationships is difficult due to their complexity and variability.

Climate change will affect the phenological development of both host species and insects, but the outcome of these changes is difficult to predict. Research has suggested that the spruce budworm has a relatively wide range of spring emergence dates such that it may to some extent accommodate a shift in host foliage availability; the picture for other insects is less clear.

The interaction among insect outbreaks and other disturbance agents will also change. Observations of the current mountain pine beetle outbreak in British Columbia suggests that a beetle-killed stand increases in flammability shortly after the trees are killed due to the persistence of dead foliage in the first few years. As the needles drop, fine fuels are reduced and flammability declines. As the stand ages, flammability increases again as dead stems fall and begin to accumulate on the ground. Stands of budworm-killed

balsam fir in Ontario reach maximum flammability 5–8 years following mortality due to crown breakage and windthrow. Flammability declines thereafter due to the decomposition of fuels and proliferation of understory vegetation, which has a higher moisture content.

A recent review of the impacts of climate change on forests provides the following summary for important insect pests in Canada[3]:

Recent research based on one of the relatively less intense climate change scenarios suggests that future outbreaks of spruce budworm could last six years longer and result in 15% more defoliation than current outbreaks. In addition, the increase in outbreak severity would occur primarily at the southern and northern margins of the spruce budworm's outbreak distribution. This is consistent with previous research that suggested that higher frequencies of outbreaks may occur at the southern margins of the species' range due to drought stress on host trees, and that an improvement in springtime synchrony between the initiation of larval feeding and bud burst could extend the range of outbreaks northwards.

The mountain pine beetle spread into central Alberta in 2006. According to most future climate scenarios, the climate of boreal pine forests will become increasingly suitable for the beetle in the near future. Thus, the spread of the mountain pine beetle into boreal pine forests east of Alberta appears likely, although the effect of this range expansion would likely be less severe than that observed recently in British Columbia due to the different spatial configuration of pine stands east of Alberta. Additionally, some research suggests that future winters may still be cold enough to limit large-scale outbreaks.

The forest tent caterpillar and the jack pine budworm cause significant damage to Canada's forests. Increased outbreaks of these species are likely to occur along the southern margins of their ranges due to drought resulting from climate change. A northward expansion in the distribution of outbreaks is also likely owing to a decreased likelihood of catastrophic loss of suitable foliage as a consequence of less frequent late spring frosts.

The gypsy moth, an alien invasive species, has spread to much of the temperate hardwood forested area of northeastern North America since its introduction in the late 1800s. Recent estimates suggest that a 1.5°C increase in mean daily temperature could result in an increase of 95 million hectares (16%) in the range of gypsy moth in Canada.

The spruce bark beetle has periodically killed large areas of mature spruce forests across Canada. Evidence indicates that the recent unprecedented outbreaks in Alaska and the Yukon have been exacerbated by climate change, which has caused the species to shift from a 2-year to a 1-year life cycle, and has resulted in temperature-induced drought stress of its host trees. It is likely that with climate change, spruce beetle impacts will increase throughout the range of its host trees for the same reasons.

Table 1 summarizes the likely regional impacts of biotic disturbance in Canada's forests.

[3] Lemprière, T.C., P.Y. Bernier, A.L. Carroll, M.D. Flannigan, R.P. Gilsenan, D.W. McKenney, E.H. Hogg, J.H. Pedlar, and D. Blain. 2008. The Importance of Forest Sector Adaptation to Climate Change. Natural Resources Canada, Ottawa, Ont., Information Report NOR-X-416E.

**TABLE 1. Scale of regional and national impact of climate change on biotic disturbance based on severity, frequency, and size of area affected. NC = no change. ? = uncertain. Scale of change in area affected by biotic disturbance: + low, ++ moderate, +++ high.[4]** (Source, see footnote 3)

| PERIOD | ATLANTIC MIXEDWOOD | BOREAL EAST | BOREAL WEST | MONTANE | PACIFIC | CANADA |
|---|---|---|---|---|---|---|
| Present | NC | NC | ++ | +++ | + | + |
| Near-term (2011–2040) | + | + | +++ | ++ | ++ | ++ |
| Medium-term (2041–2070) | ++ | ++ | +++ | ? | ++ | +++ |
| Long-term (2071–2100) | ? | ? | ? | ? | ? | ? |

## Pathogens

Forest tree diseases are comprised of a wide range of organisms (fungi, bacteria, nematodes, and parasitic plants), which live and infect trees under widely varying biological conditions. These pathogenic organisms are strongly influenced by the same environmental conditions that affect their host trees.

Typically, the two most important environmental factors in the development of forest tree diseases are temperature and moisture. However, since temperature and moisture requirements of pathogens and of their host species are variable, predicting the impacts of climate change is extremely challenging. Temperatures are expected to increase more in winter than in summer, which will likely lead to an increase in the number of frost-free days. When summer temperatures are more stressful for the tree than for the pathogen, disease often occurs. Moisture requirements of pathogens are somewhat complicated. When forest trees are water stressed, they are more susceptible to disease. In addition, both pathogens and hosts are affected by variations in climate cycles and extremes. These climatic stresses on forest trees will benefit the pathogens.

Climate change can directly affect the pathogen or indirectly affect the host and the interactions between pathogen and host. Direct effects on pathogens are likely to include increased growth, reproduction, and spread; and changes in summer or overwinter survival. Indirect effects may include changes to the host due to factors such as nutrient or water stresses. Associated vectors could also be indirectly affected, and could include changes in the distribution or life cycles of insects associated with pathogens, or changes among the different forest tree and plant populations, which could result in established plant communities becoming stressed and susceptible to disease.

Climate change is also likely to cause evolutionary change in tree and pathogen populations. Generation times of pathogens are much shorter than those of host tree species, which allows pathogens to adapt to changing conditions more rapidly. This will also likely lead to higher rates of infection and virulence, particularly where host trees are under stress.

Since the environmental conditions associated with a changing climate will vary at rates faster than trees can adapt, forest trees will be under stress and all forest types will be susceptible to pathogens.

[4] The anticipated decline in area affected, and the early transition to "unknown" in the Montane region in the near and medium terms, respectively, is a result of the unprecedented impact and imminent collapse of the current mountain pine beetle epidemic.

# ASSESSMENT OF TREE SPECIES VULNERABILITY TO CLIMATE CHANGE

The previous section provided a general overview of the biophysical impacts of climate change on tree species and the ways in which they will respond. This section provides an assessment of anticipated threats to tree species in Canada due to climatic change.

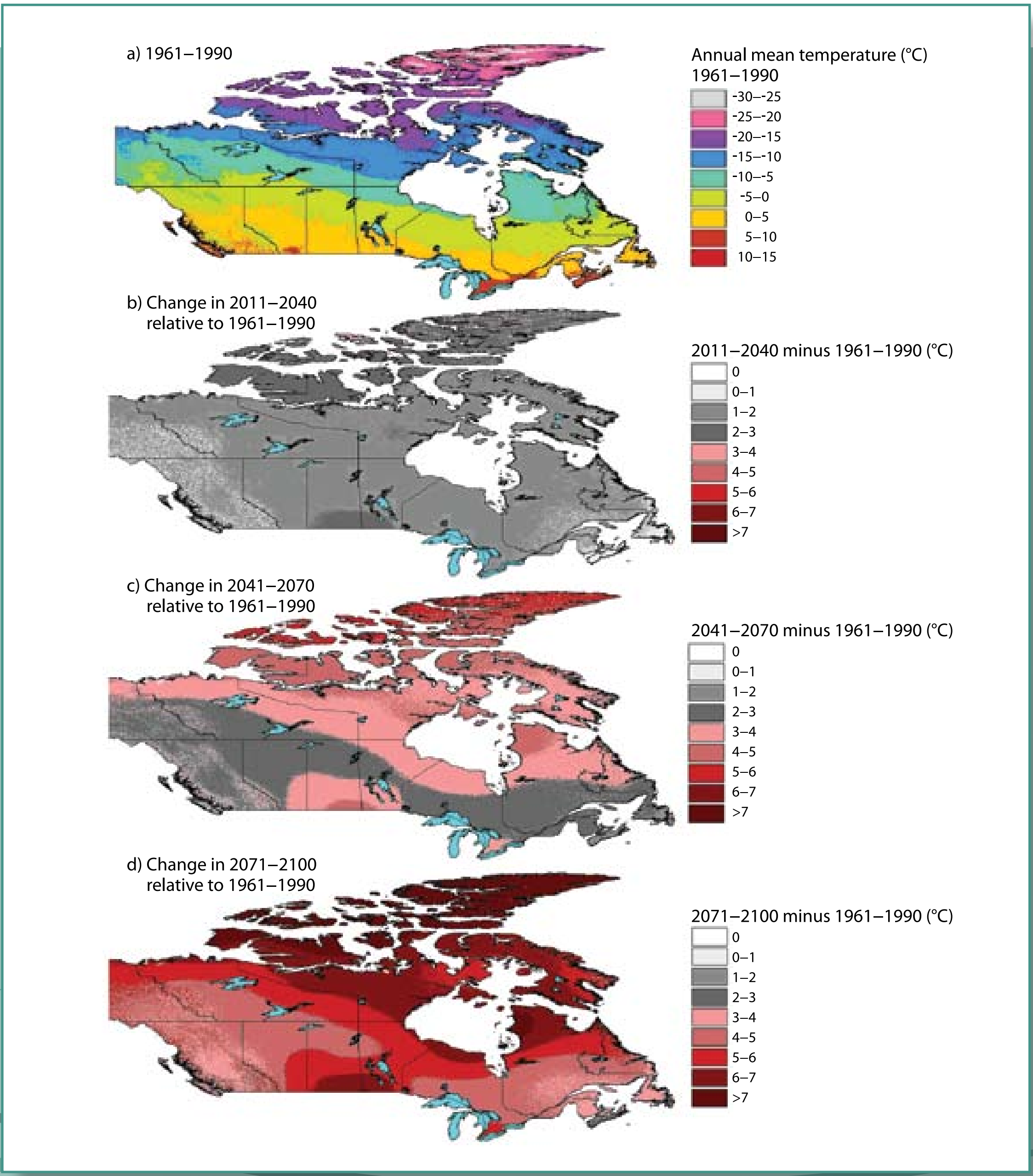
## CLIMATE TRENDS AND PROJECTIONS

All of Canada, with the possible exception of the Atlantic offshore area, is projected to warm during the next 80 years. The magnitude of warming is not known, but it will not be uniform across the country (Figure 4). Temperature increases will be greatest in the high Arctic, and greater in the central portions of the country than along the east and west coasts. It is clear that climate change must be considered from a regional perspective in order to fully understand tree species vulnerability.

On a seasonal basis, warming is expected to be greatest during the winter months. Winter warming by the 2050s is expected to be most pronounced in the Hudson Bay and high Arctic areas, and least in southwestern British Columbia and the southern Atlantic region. A decrease in the winter diurnal temperature range across the country indicates that winter nights will likely warm more than winter days. Rates of warming will be lower in the summer and fall, and summer warming is projected to be more uniform across the country.

Future precipitation is more difficult to project, and changes are generally of lower statistical significance than changes in temperature. This is reflected in the wide range of model results for projected precipitation. Annual total precipitation is projected to increase across the country during the current century. By the 2080s, projected precipitation increases range from 0 to 10% in the far south up to 40 to 50% in the high Arctic (although this latter percentage increase may not translate to a large absolute increase since the current annual precipitation in the far north is often less than 200 mm a year). Due to enhanced evapotranspiration, driven by higher temperatures, many regions, particularly western Canada, will experience summer moisture deficits despite receiving greater amounts of annual precipitation (Figure 3).

**FIGURE 4. One possible scenario of change in mean temperature across Canada (Note: this is only one of a number of possible climate change scenarios that could occur in Canada).** (reprinted with permission from Lemprière et al. 2008)



## THREAT ASSESSMENT

Canada's tree species are vulnerable to climate change for a variety of complex, interacting reasons. For example, trees species and genotypes could become increasingly maladapted, climatic envelopes will change faster than trees can adapt or migrate, site conditions will change, and the frequency, extent, and severity of disturbance will increase. Additionally, increased tree mortality and decreased forest health are expected, especially for sensitive species on poor sites. Commercially important tree species may lose their ability to compete and regenerate on some sites. Productivity gains are possible in areas that are not moisture limited (due to a longer growing season, warmer temperatures during the growing season, and $CO_2$ fertilization), but productivity will decrease in areas that become drier. Early adaptation by modifying forest management policies and practices offers the potential to both minimize negative impacts and take advantage of climate change opportunities (e.g., timber management policies and controls could be modified to take advantage of productivity gains).

Adaptation can increase the likelihood that the next generation of trees is better suited to the climatic envelopes within which they will be growing. Adaptation measures include reducing forest vulnerability through facilitated migration, managing gene pools, and taking account of future conditions when selecting species for re-establishing forests, or using other forest management activities that involve species selection. The potential for exotic species to become invasive also needs to be addressed.

All regions and forest types are threatened by climate change, but some are more vulnerable than others. The greatest warming will occur in the central and northern parts of Canada, an area dominated by boreal forest. The northern coniferous boreal forest is highly adapted to a cold climate and will experience a higher relative rate of warming than other locations. Increased wildfire activity, permafrost melting, and maladapted trees pose significant threats to northern species such as white and black spruce. Northern forests are also sparsely populated and have relatively low commercial timber value; therefore, financial investment in forest management interventions and adaptation will likely be low. The main threats to the southern boreal forest are drying (including periodic intense droughts) and increased wildfire activity. There are also concerns about the potential for mountain pine beetle to spread into jack pine forests and move across the boreal forest. However, experts are sceptical about this scenario because jack pine stands may not occur in sufficient density or extent to support a widespread outbreak, even if climates warm enough to overwintering survival of the beetle. The northern and the southwestern boreal forests are highly vulnerable to climate change. Forests in the central and eastern portions of the boreal forest region will probably experience fewer drought events but will be increasingly vulnerable to both native and introduced pests. Climate change considerations need to be incorporated into regeneration decisions across the boreal forest because of the potential for maladaptation.

The Montane Cordilleran region of central British Columbia may experience a loss of alpine ecosystems as treelines increase in elevation. Forest cover may decrease in dry areas of the southern interior of the region. Disturbance activity (fire, insects, drought, extreme weather) will increase throughout the Montane region, but there is the potential for productivity gains—at least up to 2050—in the northern portions of the region because moisture is not expected to be limiting. In summary, the southern montane forest is highly vulnerable whereas the northern montane forest is moderately vulnerable to climate change.

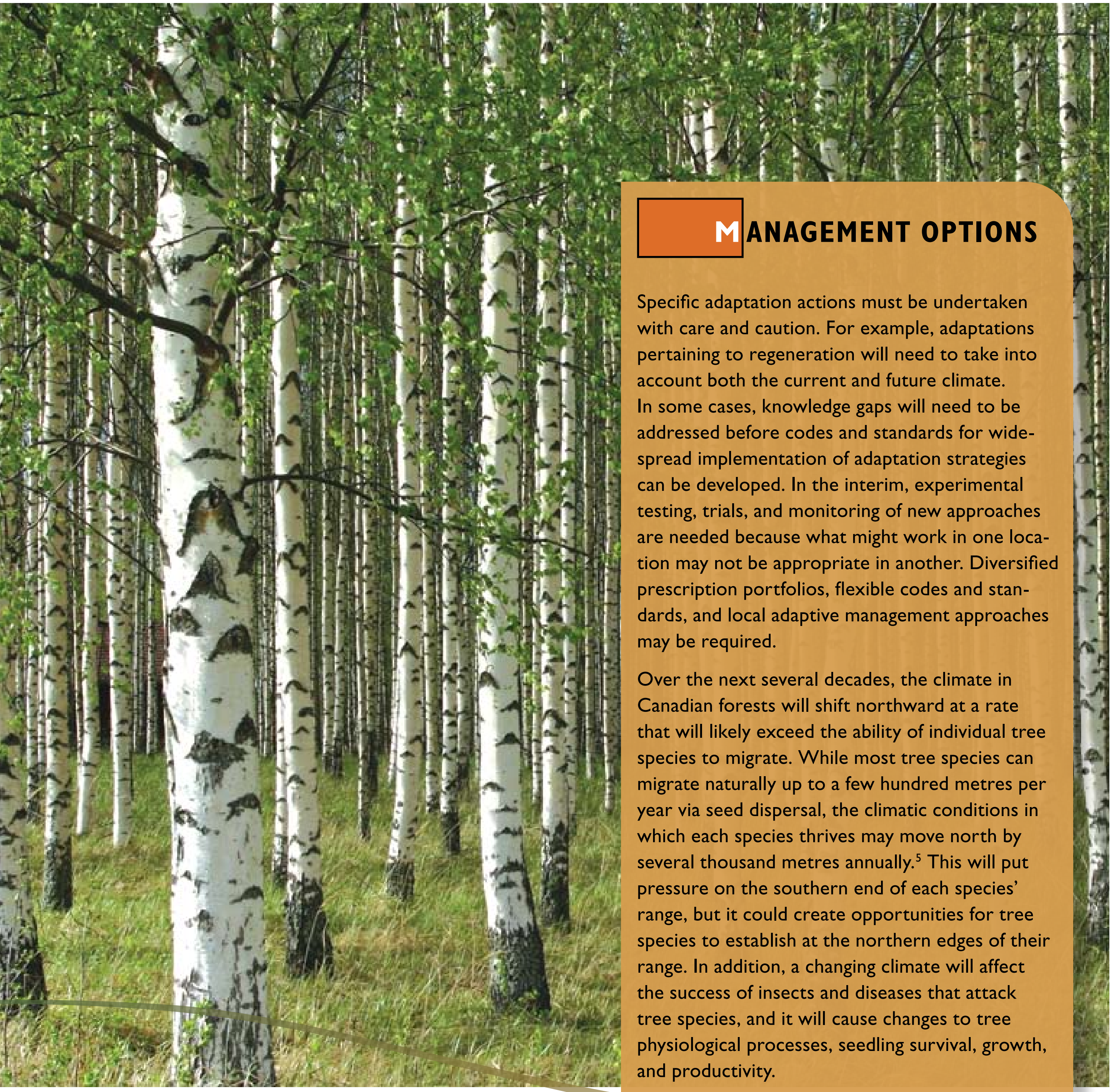
The Pacific Maritime, Mixedwood Plains, and Atlantic Maritime regions face an increased threat from extreme weather (increased frequency and intensity of severe windstorms), but the overall vulnerability of forests in these regions may be relatively lower than in other areas—at least up to 2050. However, pests (e.g., the balsam fir woolly adelgid) may continue to pose significant threats.

There will be hot spots of high vulnerability within local populations of tree species in all the regions mentioned above. For example, transition zones between these regions (and transition zones between ecosystems within the regions) will be highly vulnerable to climate changes because environmental conditions within these areas are close to the limits of species' tolerances.

Uncertainty could present a barrier to adaptation. Although changes in the composition, structure, and age of forests will certainly occur, the magnitude, location, and timing of these changes is unknown. Uncertainty about these effects is due in part to a variety of different future climate scenarios. However, there are a number of additional sources of uncertainty. Ecosystems are complex. Many interacting factors will combine to cause a particular response to future climate change, but it is unknown which factors will dominate in a given location. For example, it is unclear whether the direct effects of climate change on physiological processes will be the dominant factor in climate change responses in a certain area, or whether indirect effects, such as changes in disturbance patterns, will dominate. In fact, there is uncertainty about the net effects of all the factors noted previously, but more importantly, their cumulative effects are unknown. In addition, there is uncertainty about how much human adaptation will occur and how effective it will be. Heightened levels of uncertainty create additional challenges for effective forest management and long-term planning. Unanticipated and novel events are likely to occur. Moreover, history is no longer a guide to what will happen in the future. This is particularly important in situations where policy is based on what has worked successfully in the past. Management strategies might include explicit adoption of risk and adaptive management approaches and enhanced monitoring efforts to allow for early detection of changes. Most important, climate change considerations and uncertainty related to climate change need to be incorporated into forest management planning, policy, and decision making.

## THE CASE FOR HUMAN ADAPTATION

The relative vulnerability of Canadian tree species to climate change depends in part on the willingness of society to support adaptation, the capacity of forest management organizations to adapt, and the relative success of investment in adaptation. This review has shown that in the absence of adaptation, many of Canada's tree species are highly vulnerable. However, a strong human capacity to adapt and successful implementation of adaptation measures could reduce tree species vulnerability in managed forest landscapes. The following section describes some of the key implications for management. For detailed recommendations, see the following publications in Appendix 2: Spittlehouse and Stewart 2003; Johnston et al. 2006; Ogden and Innes 2007; Lemmen et al. 2008; Seppala et al. 2009.



## MANAGEMENT OPTIONS

Specific adaptation actions must be undertaken with care and caution. For example, adaptations pertaining to regeneration will need to take into account both the current and future climate. In some cases, knowledge gaps will need to be addressed before codes and standards for widespread implementation of adaptation strategies can be developed. In the interim, experimental testing, trials, and monitoring of new approaches are needed because what might work in one location may not be appropriate in another. Diversified prescription portfolios, flexible codes and standards, and local adaptive management approaches may be required.

Over the next several decades, the climate in Canadian forests will shift northward at a rate that will likely exceed the ability of individual tree species to migrate. While most tree species can migrate naturally up to a few hundred metres per year via seed dispersal, the climatic conditions in which each species thrives may move north by several thousand metres annually.[5] This will put pressure on the southern end of each species' range, but it could create opportunities for tree species to establish at the northern edges of their range. In addition, a changing climate will affect the success of insects and diseases that attack tree species, and it will cause changes to tree physiological processes, seedling survival, growth, and productivity.

[5] The rate of change is expected to be greatest in the north and in continental areas rather than on the coast.

Forest managers across Canada must begin to consider ways in which they can address the vulnerability of Canada's commercial tree species to climate change. The choice of adaptation options used depends on local conditions, local vulnerabilities, and management objectives. Consequently, it is not possible to make generic recommendations about management options. Rather, it will be beneficial to consider all possible options when preparing a forest management plan, and to weigh the anticipated performance of alternative options against management objectives as a means of supporting decision-making. Since there is no universally applicable measure of how to adapt to climate change, forest managers need to have sufficient flexibility to deploy the adaptation measures that are most appropriate for their local situations. Given the extent of uncertainty about climate change effects, managers will need to monitor the effectiveness of their actions and be able to modify their actions quickly as new information becomes available. The discussion below presents a range of possible management options for addressing tree species vulnerability on managed forest lands. Options are presented by the context within which decisions are made at a species level (e.g., reforestation, genetic conservation, forest productivity, and forest health).

Management options for reducing the vulnerability of Canada's commercial tree species to climate change in managed forest lands are summarized here according to five management objectives:

- reforest managed forest land
- conserve genetic diversity
- maintain species productivity
- maintain forest health
- enhance adaptive capacity

## REFORESTATION

Regeneration represents the point in a tree's life cycle when it is most vulnerable to environmental impacts, including climate variability and change. While well-established adult trees can often withstand drought events and other disturbances, seedlings are highly vulnerable. In addition, the regeneration phase is the point at which forest management has the ability to influence species selection, and tree establishment and growth. There are a number of species-specific options available to managers when they are considering how and where to undertake regeneration activities.

As mentioned previously, most tree species will probably be unable to migrate fast enough to accompany changes brought on by a changing climate because their natural migration rates are at least an order of magnitude too slow. Therefore, assisted migration may provide managers with several options for introducing planting stock that is better adapted to the new climate. Three aspects of assisted migration that are relevant to forest management have been identified[6]:

**LOWER RISK**

- Assisted population expansion: movement of populations within a species' range to improve productivity and health in new climates
- Assisted range expansion: regional expansion of northern, inland, or upper elevational limit of species for reforestation to track climatic niches
- Translocation of exotics: inter-regional, transcontinental, or intercontinental movement of species

**HIGHER RISK**

[6] Dr. Sally Aitken, Department of Forest Sciences, University of British Columbia, pers. comm.

Assisted population expansion would involve the movement of populations within the species current range—e.g., from the southern edge of its range to the northern portion. Analysis of provenance test data for several species has provided information on how far populations would need to be moved within their current range in order to grow in a suitable future climate. These analyses have been conducted for lodgepole pine in British Columbia; white and black spruce, lodgepole and jack pine, and tamarack in Alberta; jack pine in Ontario; and black and white spruce in Québec. There is a general understanding of how various populations of these species may fare with respect to future climate conditions. However, managers must keep in mind that most historical provenance test data do not account for the effects of future increases in atmospheric $CO_2$, and do not include the full extent of climatic extremes or a species' range. Managers must also be aware of the trade-off that is inherent in any type of assisted migration: the climate distance that populations or species are migrated will have to be small enough to allow for good survival at establishment but large enough to ensure good adaptation toward the end of the rotation when mean annual increment is maximum. The data to adequately answer how best to address this trade-off are currently lacking.

Assisted range expansion is a somewhat riskier option than assisted population expansion. Populations are moved to extend beyond their historical range in anticipation of future climatic conditions, while remaining contiguous with the species' original distribution. Provenance data are less helpful in this option because they do not generally include plantings outside of species' historical ranges. In this case, other species will already be established in the new location and will compete to some extent with the introduced populations. This option also requires a sophisticated understanding of how species' climatic envelopes will change. This understanding is currently at an early stage for most species.

Translocation of exotics is the riskiest option for assisted migration. This entails introducing a species to a location in which it has not occurred in the past. While the species may be adapted to conditions expected to occur in the future at the new location, the understanding of how climatic conditions will change is highly uncertain, especially at the scale of individual stands where reforestation decisions will be applied. In addition, exotic species may become invasive, and are likely to bring along associated pests and diseases which may react differently in the new location (i.e., they may have higher virulence or undergo population outbreaks). Many conservation biologists are strongly opposed to this option except where invasiveness and pest issues are well understood; however, this is generally not the case for most tree species.

Reforestation could also include: emphasizing species or populations that have the genetic ability to tolerate a wide range of environmental conditions; reforesting immediately after harvesting with most suitable species and genotypes where natural regeneration shows low diversity; and increasing species and genetic diversity in plantations to reduce risk and increase the likelihood that some will survive. Reforestation following large disturbances (e.g., fires) could provide an opportunity to establish better-adapted genotypes over large areas.

Finally, data from existing provenance tests could be analyzed for their use in understanding species and population genetic variability, and new tests could be established for most commercial tree species in Canada. While these tests take a few decades to yield results, the sooner they are established, the sooner the benefits can be realized. In order to get the most out of these data, the feasibility of establishing a centralized repository of national provenance data should be evaluated.

### CONSERVE GENETIC DIVERSITY

A number of management options can be used to conserve genetic diversity, including:

- using silvicultural systems that maintain genetic and species diversity;
- creating and maintaining corridors that facilitate the migration of tree species and genotypes (as well as other plant and animal species);
- creating artificial reserves; and
- using *ex situ* collections to preserve rare populations.

### MAINTAIN SPECIES PRODUCTIVITY

Establishing healthy and productive stands is an obvious way of helping ensure trees are robust in the face of climate change. Managers could work towards this by:

- maintaining a diversity of age classes and species where it does not increase susceptibility to insects, disease, or fire;
- thinning stands on drought-prone sites to reduce water use where it will not increase susceptibility to windthrow or disease;
- controlling undesirable plant species that are likely to become more competitive in a changed climate;
- focusing management on currently productive sites and those likely to remain more productive under future climates, and reducing efforts on poor sites;
- favouring drought-tolerant species in drought-prone areas; and
- working towards shortening rotation ages and replanting with more robust genotypes.

Where economic conditions allow, the use of intensively managed plantations dedicated to wood supply would focus efforts on a more productive but smaller forest estate which could be managed to reduce the impacts of climate change.

## MAINTAIN FOREST HEALTH

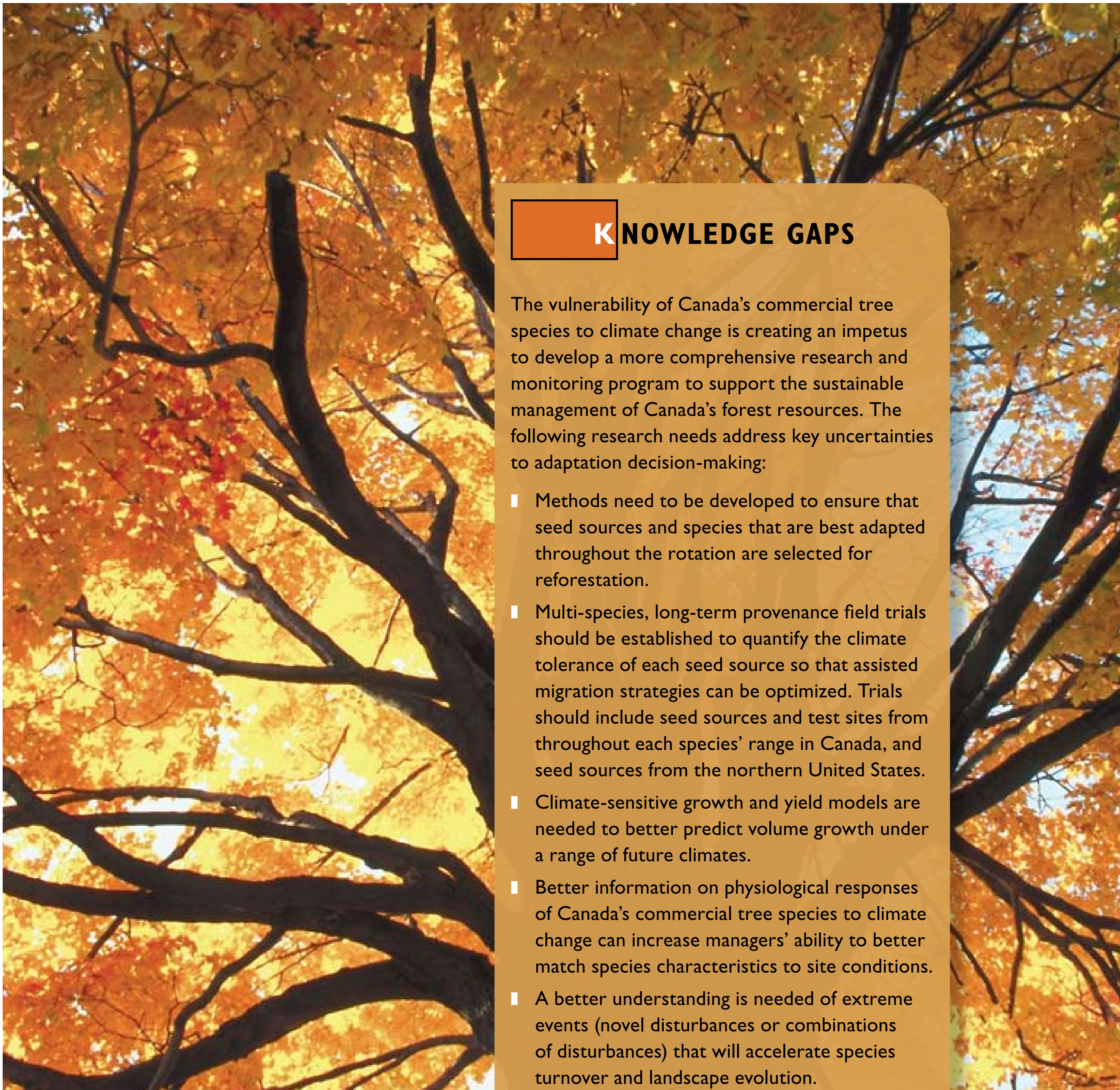
In this era of rapid environmental change, it is critical that enhanced forest health monitoring networks are established and maintained to provide early warning signals for impending climate change impacts. These networks need to collect data on both pathogen population outbreaks and changes in host and pathogen phenology. An excellent example of such a network is the Climate Impacts on the Productivity and Health of Aspen Network. It is currently maintained by the Canadian Forest Service, and extends throughout the range of aspen from the Northwest Territories across the Prairie provinces to northwestern Ontario. In addition, forest health can be maintained or enhanced by:

- focusing harvest activities on stands that are most susceptible to pests, or conducting sanitation cutting in stands that are already affected;
- developing genotypes that are drought tolerant and resist insects and disease;
- using prescribed burning to reduce fire risk and forest vulnerability to insect outbreaks; and
- putting more effort into integrating climate change models with biological models of phenology.

## ENHANCE ADAPTIVE CAPACITY

The ability of tree species to adapt has both a biological component (e.g., migration and adaptation) and a human component (i.e., management). While the understanding of climate change vulnerability and potential adaptation options is rapidly increasing, the development of adaptive capacity among forest managers and forest management institutions remains to be done. Adaptive capacity can be enhanced by:

- sharing adaptation best practices across jurisdictions;
- incorporating knowledge of species vulnerability in decision-making that involves reforestation and silviculture;
- encouraging changes in society's expectations about future forest values and benefits so that they include tree species vulnerability to climate change;
- developing technology to make use of different wood quality and tree species composition;
- reducing reliance on historical observations and plot measurements to predict what will happen in the future; and
- developing reliable species- and stand-level process models for predicting future growth and yield.



## KNOWLEDGE GAPS

The vulnerability of Canada's commercial tree species to climate change is creating an impetus to develop a more comprehensive research and monitoring program to support the sustainable management of Canada's forest resources. The following research needs address key uncertainties to adaptation decision-making:

- Methods need to be developed to ensure that seed sources and species that are best adapted throughout the rotation are selected for reforestation.
- Multi-species, long-term provenance field trials should be established to quantify the climate tolerance of each seed source so that assisted migration strategies can be optimized. Trials should include seed sources and test sites from throughout each species' range in Canada, and seed sources from the northern United States.
- Climate-sensitive growth and yield models are needed to better predict volume growth under a range of future climates.
- Better information on physiological responses of Canada's commercial tree species to climate change can increase managers' ability to better match species characteristics to site conditions.
- A better understanding is needed of extreme events (novel disturbances or combinations of disturbances) that will accelerate species turnover and landscape evolution.

- Climate models and scenarios need to be enhanced to assess species adaptation strategies across a wide range of plausible future conditions. It is important to recognize the uncertainties inherent in climate and ecosystem models. Decision support tools that explicitly address these uncertainties are required.
- The benefits and risks of planting species mixtures at higher densities in anticipation of higher mortality need to be assessed.
- Research is needed on potential future species distributions. This will also require better modelling tools. This information will allow better long-term planning for future forest composition, and may provide direction for experimental plantings of new populations or species in anticipation of the future climate.
- More data from provenance tests need to be analyzed, which will increase their value in developing approaches to assisted migration.
- Climate-based seed transfer systems need to be developed.
- Limitations and impacts of climate on seedlings and germinants need to be determined.
- The relationship between phenology and climate change and variability needs to be investigated.
- Key environmental thresholds for species need to be identified, and which thresholds will be exceeded and when need to be determined, if possible.
- Better information on insect physiology and how it will determine behaviour under future climates is needed.
- Models combining physiology and climatic data may allow some general predictions of future species distributions to be made.
- Better information on the coupling of insect and host tree phenology, its effect on pollinators, and how that will change under future climate conditions is also important.

# CONCLUSIONS

## KEY FINDINGS AND THEIR IMPLICATIONS FOR MANAGEMENT

Trees species that are dominant within the northern boreal forest (white and black spruce), southwestern boreal forest (aspen in the aspen parkland and conifers in the southern parts of the boreal plains), and the southern Montane Cordilleran forest in southern British Columbia will be the most vulnerable to climate change in the foreseeable future. However, local populations of tree species will be vulnerable in transition zones between all forest regions and between ecosystems within forest regions. Therefore, all species in Canada will probably be affected.

Changes in current climatic niches for tree species across Canada will, in many cases, change at a pace that exceeds the ability of most tree species to adapt or migrate. In most cases, changes will be within physiological tolerance limits of existing trees, at least for perhaps the next few decades. However, given that trees take a long time to mature, future climate change could have important implications for trees that are becoming established today and which will form the next generation of trees; therefore, it is particularly important that climate change considerations be incorporated into current reforestation practices, policies, and approaches. For the next several decades, changes in disturbance regimes due to climate change (i.e., fire, drought, insect outbreaks) will be a dominant force affecting the existing forest.

The increased risk and uncertainty associated with climate change presents a significant challenge for forest management. Management costs may rise, failure to comply with regulations could increase, and historical relationships may not be reliable for projecting the future. Forest management is particularly vulnerable where there is reliance on static models or indicators because they do not address the dynamic nature of forest ecosystems. This should not, however, be an excuse for inaction.

Actions that could facilitate adaptation include:

- mainstreaming climate change into forest management using a systems approach (i.e., giving consideration to climate change during planning, reforestation, stand tending, and harvesting);
- facilitating assisted migration of tree species and seed sources where data support these activities;
- enhancing species adaptation by developing, sharing, and adopting climate sensitive best management practices;
- reducing the risk of losses to catastrophic disturbance through harvesting and "climate conscious" management;
- enhancing monitoring to ensure the early detection of the impacts of climate change and the effectiveness of adaptation measures;
- incorporating vulnerability analysis, risk analysis, and adaptive management into forest management practices; and
- continually identifying key knowledge gaps, institutional arrangements, and policies that pose significant barriers to adaptation, and taking actions to rapidly address them.
- Finally, forest harvest operations could be directed towards the most susceptible stands to reduce the risk of large insect outbreaks.

## RESEARCH NEEDS PERTAINING TO TREE SPECIES

Scientists have suggested that additional research is needed in a number of areas to further our understanding of the impacts of climate change on tree species. These areas include:

Further research on possible future species distributions is needed. This will require better modelling tools, especially dynamic vegetation models. This information will allow better long-term planning for future forest composition, and may provide direction for experimental plantings of new populations or species in anticipation of the future climate.

Better information on insect physiology and how it will determine behaviour under future climates is needed. Models combining physiology and climatic data may allow some general predictions of future insect distributions to be made. Better information on the coupling of insect and host tree phenology, and how that will change under future climates, is also important.

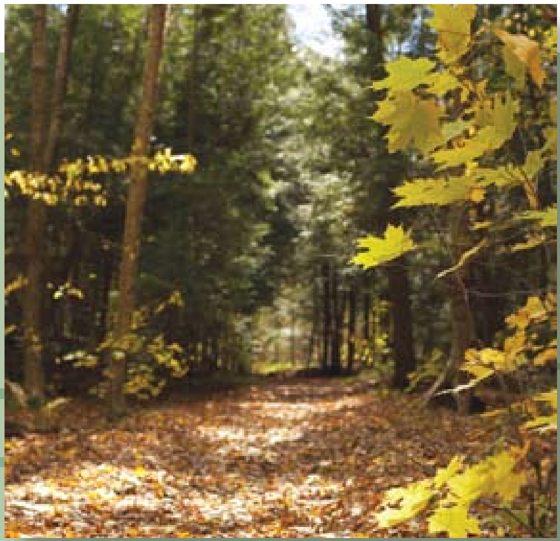
Better information on tree physiology can enhance managers' abilities to match species characteristics, such as drought tolerance or frost tolerance, to site conditions. Climate-sensitive growth and yield models are needed to better predict volume growth under a range of future climates. This new information could enable forest managers to begin thinking about reallocating management efforts now. Ongoing monitoring of tree growth, establishment success, and mortality will provide clues about the nature of climate impacts as they start to occur.

Analyzing additional data from provenance tests will help in developing approaches to assisted migration. Where data are lacking, new tests that sample the entire species range and its climatic characteristics should be established. Climate-based seed transfer zones could be developed. Experimental plantings of new populations could be undertaken as long as the risk of invasiveness and introduction of new pests has been assessed. Other specific research requirements include:

- developing a better understanding of the role of genetic variation in the climatic tolerances of tree species;
- identifying the role of silvicultural treatments in mitigating stand vulnerability to fire, insects, and drought;
- determining the limitations and impacts of climate on seedlings;
- developing a better understanding of the extent of $CO_2$ fertilization for various species and its effects on reducing climate impacts;
- identifying key thresholds for species and ecosystem processes, and determining which thresholds will be exceeded and when, if possible;
- identifying the relationship between phenology and climate change and variability;
- basing planning on the fact that vegetation types and communities will be forced by nature to become more dynamic as assemblages erode and accrete; and
- developing a better understanding of extreme events (novel disturbances or combinations of disturbances) that will accelerate species turnover and landscape evolution.

## NEXT STEPS: MOVING BEYOND TREES TO FORESTS AND THE FOREST SECTOR

This report focuses on climate change and the vulnerability of commercially important tree species in Canada. This is an important first step; however, the CCFM acknowledges that an improved understanding of tree species vulnerability provides only a partial picture. As suggested in the CCFM document *A Vision for Canada's Forests: 2008 and Beyond*, climate change is expected to affect forest landscapes and the forest sector. It will also affect the full array of forest management objectives that are part of sustainable forest management, and an array of forest values and stakeholders (forest industry, forest-based communities, protected areas, First Nations populations, wildlife, water, public health and safety, timber supply, etc.). Therefore, a comprehensive approach that considers climate change in a broader context will be needed. It is the intention of the CCFM to follow up this study with an assessment that focuses on these broader issues. This will include an evaluation of the potential impacts of climate change at a broader landscape scale and an assessment of how these changes could affect forest assets and values. Phase 2 will develop a better understanding of climate change vulnerabilities foreseeable for sustainable management of Canada's forests at the national level. It will also identify potential approaches to adaptation to reduce these vulnerabilities. A goal of the next phase is to develop a framework and guidance documents to assist jurisdictions and forest practitioners to incorporate climate change considerations into Sustainable Forest Management in Canada. This next phase will build upon earlier ecological and socio-economic assessments of the Canadian Council of Forest Ministers.



# APPENDIX I. TREE SPECIES OF COMMERCIAL VALUE IN CANADA

True Fir: *Abies*
Balsam Fir: *A. balsamea*
Grand Fir: *A. grandis*
Alpine/Subalpine Fir: *A. lasiocarpa*
Amabilis Fir: *A. amabilis*
Noble Fir: *A. procera*

Pine: *Pinus*
Eastern White Pine: *P. strobus*
Red Pine: *P. resinosa*
Jack Pine: *P. banksiana*
Lodgepole Pine: *P. contorta*
Whitebark Pine: *P. albicaulis*
Western White Pine: *P. monticola*
Ponderosa Pine: *P. ponderosa*
Limber Pine: *P. flexilis*
Western White Pine: *P. monitcola*
Pitch Pine: *P. rigida*
Scots Pine: *P. sylvestris*
Austrian Pine: *P. nigra*

Birch: *Betula*
White (Paper) Birch: *B. papyrifera*
Yellow Birch: *B. alleghaniensis*
Grey Birch: *B. populifolia*

Maple: *Acer*
Sugar Maple: *A. saccharum*
Black Maple: *A. saccharum spp. nigrum*
Silver Maple: *A. saccharinum*
Red Maple: *A. rubrum*
Manitoba Maple: *A. negundo*
Norway Maple: *A. plantanoides*

Cedar: *Thuja*
Western Redcedar: *T. plicata*
Eastern White-Cedar: *T. occidentalis*

Hemlock: *Tsuga*
Eastern/Canadian Hemlock: *T. canadensis*
Mountain Hemlock: *T. mertensiana*
Western Hemlock: *T. heterophylla*

Spruce: *Picea*
White Spruce: *P. glauca*
Black Spruce: *P. mariana*
Norway Spruce: *P. abies*
Englemann Spruce: *P. engelmannii*
Hybrid Spruce
Red Spruce: *P. rubens*
Sitka Spruce: *P. sitchensis*

Yew: *Taxus*
Western Yew: *T. brevifolia*

Walnut: *Juglans*
Black Walnut: *J. nigra*

Aspen, Cottonwood, Poplar: *Populus*
Balsam Poplar: *P. balsamifera*
Black Poplar: *P. nigra*
Largetooth Aspen: *P. grandidentata*
Trembling Aspen: *P. tremuloides*
Eastern Cottonwood: *P. deltoides*

Cherry: *Prunus*
Wild Black Cherry: *P. serotina*
Pin Cherry: *P. pensylvanica*

Cypress: *Chamaecyparis*
Yellow Cedar: *C. nootkatensis*

Douglas-fir: *Pseudotsuga*
Douglas-fir: *P. menziesii*

Larch: *Larix*
Alpine Larch: *L. lyallii*
Tamarck/Eastern Larch: *L. laricina*
Western Larch: *L. occidentalis*
Japanese Larch: *L. kaempferi*
European Larch: *L. decidua*

Beech: *Fagus*
American Beech: *F. grandifolia*

Oak: *Quercus*
White Oak: *Q. alba*
English Oak: *Q. robur*
Bur Oak: *Q. macrocarpa*
Swamp White Oak: *Q. bicolor*
Chinquapin Oak: *Q. muehlenbergii*
Black Oak: *Q. velutina*
Red Oak: *Q. rubrus*
Northern Pin Oak: *Q. ellipsoidalis*
Garry Oak: *Q. garryana*

Ash: *Fraxinus*
White Ash: *F. americana*
Red Ash: *F. pennsylvanica*
Black Ash: *F. nigra*

Elm: *Ulmus*
White Elm: *U. americana*

Miscellaneous
Tulip Tree: *Liriodendron tulipifera*
American Basswood: *Tilia americana*
Shagbark Hickory: *Carya ovata*
Black Locust: *Robinia pseudoacacia*
Hackberry: *Celtis occidentalis*
Willow: *Salix spp.*
Ironwood: *Ostrya virginiana*

# APPENDIX 2. OTHER RESOURCES

For additional information, readers may find the following resources useful; however, this is not a comprehensive list of available literature.

Canadian Council of Forest Ministers (CCFM). Innovation Working Group. 2008. Adapting to climate change: exploring a framework for action. Work. Pap.

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# IMAGE CAPTIONS AND CREDITS

*Page 4*
Caption: Spruce and pine beetle infestations in southwest Yukon.
Photo credit: Government of Yukon

*Page 6*
Caption: Crews label, extract and bundle containerized nursery seedlings prior to planting them in field test sites as part of an assisted migration adaptation trial in BC.
Photo credit: Michael Carlson

*Page 8*
Caption: Climate change will impact entire ecosystems such as this spruce bog in central Ontario.
Photo credit: Paul A. Gray

*Page 11*
Caption: Based on the climate parameters predicted for Prince Edward Island by the end of the century, white spruce (*Picea glauca*) will be outside of its climatic envelope.
Photo credit: P.E.I. Department of Environment, Energy and Forestry

*Page 15*
Caption: Provenance test of Douglas fir in northwest BC showing dramatic differences in growth and survival of among populations. Compare the population in the foreground and the population in the background.
Photo credit: Barry Jaquish

*Page 16*
Caption: White spruce seedling in a provenance test near Revelstoke, BC.
Photo credit: Barry Jaquish

*Page 17*
Caption: Tree species included in an assisted migration adaptation trial in BC.
Photo credit: Michael Carlson

*Page 18*
Caption: Jack Pine and Black Spruce at the northern end of their range in the Northwest Territories.
Photo credit: Government of the Northwest Territories

*Page 19*
Caption: Dead trembling aspen on the South Saskatchewan River near Batoche.
Photo credit: Michael Michaelian

*Page 21*
Caption: Bronze poplar borer, *Agrilus liragus*, galleries.
Photo credit: Michael Michaelian

*Page 27*
Caption: Provenance differences in a 5 year old white/Engelmann spruce trial.
Photo credit: Lisa Vandervelde

*Page 29*
Caption: Crews planting white spruce provenance test near Terrace, BC.
Photo credit: Barry Jaquish

*Page 30*
Caption: A Douglas-fir from Vernon, BC, replanted in Los Angeles, California. Long distance transfer, particularly to environments much warmer than that in which trees evolved, may presage impacts of extreme climate warming to native forests in BC.
Photo credit: Michael Carson

*Page 31*
Caption: Climate change will likely impact the distribution and growth rate of many trees in Canada.
Photo credit: Paul A. Gray

*Page 36*
Caption: A lodgepole pine provenance test ravaged by mountain pine beetle.
Photo credit: Lorraine MacLauchlan