CLIMATE CHANGE AND CANADA'S FORESTS

FROM IMPACTS TO ADAPTATION




Tim Williamson, Steve Colombo, Peter Duinker, Paul Gray, Ryan Hennessey,
Daniel Houle, Mark Johnston, Aynslie Ogden, and Dave Spittlehouse

SUSTAINABLE FOREST MANAGEMENT NETWORK
RÉSEAU DE GESTION DURABLE DES FORÊTS

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FOREWORD

Recent events indicate that climate change is already having a significant impact on Canada's forests. These unprecedented events include the severe 2003 and 2004 fire seasons in British Columbia and the Yukon, the recent national drought, the mountain pine beetle epidemic, and reduced winter harvest opportunities being experienced in many areas. Future climate change has the potential for more pronounced impacts on the capacity of our forests to provide the many goods and services we value them for. Forest managers will experience the impacts first-hand and they need the best information available on what climate change means to them so that they can develop and implement adaptation measures.

The Sustainable Forest Management Network and Natural Resources Canada / Canadian Forest Service are pleased to collaborate on *Climate Change and Canada's Forests: From Impacts to Adaptation.* Based on the work of the forestry authors of the recently released Canadian national assessment[1], this report summarizes the current state of knowledge of current and future impacts of climate change and its implications for forest management.

Innovative research and knowledge exchange are essential for Canada's forest industry as it adapts to a changing climate. The Sustainable Forest Management Network and Natural Resources Canada / Canadian Forest Service are committed to providing forest managers with timely research findings about the implications of climate change on our ability to sustainably manage Canada's forests.

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[1] *From Impacts to Adaptation: Canada in a Changing Climate 2007*
http://adaptation.nrcan.gc.ca/assess/2007/index_e.php

ABSTRACT

Climate change is already affecting Canada's forests. Current visible effects include changes in the frequency and severity of disturbances (such as fires, drought, severe storms, and damaging insect and disease attacks): other less visible changes such as change in the timing of spring bud burst are also underway. One of the consequences of future climate change will be further increases in the frequency and severity of extreme weather events and disturbances. Changes in productivity, species composition, and age- class distribution are also expected. Moisture and temperature are key factors affecting productivity. Productivity is likely to decrease in areas that are now or will become drier; productivity is expected to increase (at least in the near term) in northern areas that are currently limited by cold temperatures. An important consideration, however, is that genotypes tend to be finely adapted to local climates and potential productivity gains may not be realized if forest managers don't match genotypes to suitable climates. A higher percentage of the forests will be in younger age classes, and the frequency of early succession species and species adapted to disturbance will increase. Climatically suitable habitats for most species will move northward and will increase in elevation but the actual movement of species will lag behind the rate of movement of climatic niches. Climate change has implications for both current and future timber supply. The net impact of climate change on timber supply will vary from location to location. The recent mountain pine beetle event shows that climate-related factors can have dramatic effects on timber supply in a relatively short time period. Climate change will impact harvest operations. A significant portion of the harvest in Canada occurs in the winter when the ground is frozen. Harvesting on frozen ground allows for access to wetlands, reduces soil disturbance, and decreases costs of delivered wood. The magnitudes of change in climate that will be faced by Canada's forests and forest management sector and the consequent scale of expected impacts have no historical analogue. Canada's forest sector will need to adapt and it will need to do so without the benefit of prior experience. Forest managers can expect the unexpected and they can expect that change will be ongoing and unrelenting. Some general recommendations for beginning to address climate change in Canada's forest sector include enhancing the capacity to undertake integrated assessment of vulnerabilities to climate change at various scales; increasing resources to monitor the impacts of climate change; increasing resources for impacts and adaptation science; reviewing forest policies, forest planning, forest management approaches, and institutions to assess our ability to achieve social objectives under climate change; embedding principles of risk management and adaptive management into forest management; and maintaining or improving the capacity for communicating, networking, and information sharing with the Canadian public and within the forest sector.

RÉSUMÉ

Les changements climatiques affectent déjà les forêts du Canada. Les effets actuels les plus visibles prennent la forme d'une modification de la fréquence et de la gravité des perturbations (feux, sécheresses, tempêtes violentes, infestations d'insectes et maladies). Mais d'autres changements moins évidents sont déjà présents, notamment dans la période de débourrement au printemps. L'une des conséquences des changements climatiques à venir se présentera comme une augmentation supplémentaire de la fréquence et de la gravité des dérèglements et des manifestations extrêmes des conditions météorologiques. On s'attend également à des changements dans la productivité et la composition forestière et dans la distribution des classes d'âge. L'humidité et la température sont des facteurs clés de la productivité. On s'attend à ce que la productivité diminue dans les zones qui sont déjà sèches ou qui le deviendront, mais qu'elle augmente (du moins à court terme) dans les zones nordiques où les températures froides sont actuellement des facteurs limitants. Il est cependant important de tenir compte du génotype qui a tendance à être étroitement adapté au climat local. Les gains de productivité potentiels pourraient donc ne pas se réaliser à moins que les aménagistes forestiers ne fassent correspondre le génotype au climat approprié. Les forêts comprendront une proportion accrue de jeunes classes d'âges, d'essences pionnières et d'essences adaptées aux perturbations. Les habitats convenant à la plupart des essences sur le plan climatique vont se déplacer vers le nord et vont monter en altitude, mais le déplacement réel des essences sera retardé, car il ne pourra suivre le rythme de déplacement des niches climatiques. Les changements climatiques ont également des répercussions sur l'approvisionnement forestier, actuel et futur, mais le résultat net variera d'un endroit à l'autre. Le phénomène récent du dendroctone du pin ponderosa démontre que les facteurs reliés au climat peuvent avoir des effets considérables sur l'approvisionnement en bois dans une période relativement courte. Les changements climatiques vont avoir un impact sur les opérations d'exploitation forestière. Une partie importante de la coupe au Canada se fait en hiver quand le sol est gelé. Ce procédé permet l'accès aux zones humides, réduit la perturbation du sol et diminue les coûts de transport du bois. L'ampleur des changements climatiques auxquels devront faire face les forêts et le secteur forestier du Canada, ainsi que l'étendue des impacts prévus, n'ont aucun analogue dans l'histoire. Le secteur forestier du Canada devra s'adapter et il devra le faire sans l'avantage d'une expérience antérieure. Les aménagistes forestiers doivent prévoir l'imprévisible et s'attendre à ce que les changements soient continus et se poursuivent sans relâche. Le rapport présente quelques recommandations générales comme premier pas dans la lutte contre les changements climatiques dans le secteur forestier du Canada, notamment améliorer les capacités permettant d'entreprendre à différentes échelles des évaluations intégrées des éléments de vulnérabilité devant les changements climatiques; augmenter les ressources affectées à la surveillance des impacts des changements climatiques et celles qui sont destinées à la recherche scientifique sur l'impact et l'adaptation; réexaminer les politiques forestières, la planification forestière, les approches d'aménagement forestier, ainsi que les institutions pour déterminer si nous sommes en mesure de réaliser des objectifs sociaux compte tenu des changements climatiques; enchâsser les principes de gestion du risque et de gestion adaptative dans l'aménagement forestier; et préserver ou améliorer les capacités de communication, de réseautage et de partage de l'information avec tous les intervenants, notamment la population canadienne et les milieux forestiers.

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EXECUTIVE SUMMARY

The forest sector in Canada is vulnerable to climate change, because of the expected magnitude of climate change at Canada's northern latitude, the sensitivity of Canada's forest ecosystems to climate change, the long growing cycles of trees and the importance of forests and the forest sector to Canadians. The purpose of this report is to provide information to forest managers to assist them in identifying and assessing potential impacts of climate change and requirements and options for adaptation. The report is based on contributions by the authors to the forestry sections of the recent Canadian national assessment report titled "From Impacts to Adaptation: Canada in a Changing Climate 2007."[2]

Impacts of climate change on Canada's forests

Climate change is already affecting Canada's forests. The most visible impacts are in the form of changes in the frequency and severity of disturbances (such as fires, drought, severe storms, and damaging insect and disease attacks). For example, the current unprecedented outbreak of the mountain pine beetle in British Columbia and Alberta, the recent spruce bark beetle outbreak in the Yukon, the dothistroma needle blight outbreak in northwestern British Columbia, aspen dieback in the Prairies, unprecedented levels of fire activity in the western boreal forest, and the recent occurrence of record forest fire seasons in the Yukon and British Columbia have been linked, at least in part,[3] to recent climate change. Much more subtle effects are also being observed. For example, the length of the growing season is increasing, bud burst in sugar maple is occurring earlier, the flowering period of aspen is occurring earlier, and tree lines are moving upward in elevation. These examples show that impacts of climate change are already occurring and they provide a basis for beginning to understand how future climate change will affect Canada's forests.

Extreme weather and climate

Canada's climate will continue to change over the next 100 years and the rate of change is expected to be substantially higher than that over the previous 100 years. One of the consequences of ongoing climate change will be further increases in the frequency and intensity of extreme weather and climate. For example, the length, frequency, and severity of drought events will likely increase; this will have major consequences for

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[2] See Lemmen, D.S.; Warren, F.J.; Lacroix, J.; Bush, E., editors. 2008. From impacts to adaptation: Canada in a changing climate 2007. Government of Canada, Ottawa, ON. Available at: <http://adaptation.nrcan.gc.ca/assess/2007/index_e php> (English) and http://adaptation.nrcan.gc.ca/assess/2007/index_f.php> (French) accessed 12 Aug. 2008.

[3] Impacts attributed to climate change are often the result of multiple interacting factors occurring simultaneously. For example, it has been suggested that previous land use activities, fire suppression, and forest management resulted in a relatively even-aged lodgepole pine forest in central British Columbia dominated by the age classes that are most susceptible to the mountain pine beetle. Recent climate change resulted in range expansion of the beetle. These factors combined have contributed to the outbreak.

forests across Canada but particularly in areas that are already moisture limited such as the southern interior of British Columbia and the southern boundary of the boreal forest in western Canada. Windstorms and intense precipitation events are expected to increase in frequency and intensity, resulting in an increase in blowdown and flood risk.

Forest fire

Climate change will significantly increase forest fire activity. Researchers have found that the average annual area burned nationally could increase by 74% to 118% over current values by the latter part of this century. There is, however, wide variation in the extent to which fire activity is expected to increase in different regions. For example, the rate of increase in fire activity will be lower in Atlantic Canada and in the moister eastern portions of the boreal forest whereas it will be higher in the forests of western Ontario and western Canada.

Insects and disease

Insects and disease are important agents of change and renewal in forests. They can also be highly destructive during outbreaks. Climate is a key factor affecting the frequency, intensity, and duration of outbreaks and also the geographic range of particular species. The response to climate change will vary from species to species; however, for insects and diseases as a group, climate change will almost certainly result in more frequent, more widespread, more intense, and longer lasting outbreaks that in turn have the potential for significant negative impacts on host tree species that may already be stressed by altered climatic regimes. Insect species with the potential for increased economic impacts under climate change include the mountain pine beetle, the larch sawfly, the spruce bark beetle, the jack pine budworm, the spruce budworm, the gypsy moth, the forest tent caterpillar, and the large aspen tortrix. Climate change is also likely to increase the risk that exotic insects and diseases will become established in Canadian forests.

Disturbance interactions

Climate change may result in multiple, interacting disturbances that occur simultaneously, with impacts beyond those of single disturbances. For example, insect and disease damage can result in an increase in wildfire risk, or events like drought can put stress on trees, making them more susceptible to insects and disease attack. These interactions are complex and difficult to predict. They are, however, potentially significant.

Productivity

The net effects of climate change on productivity will vary from location to location and over time. Temperature, moisture, nutrient availability, and atmospheric CO_2 concentrations affect rates of photosynthesis and respiration, phenology, reproduction, growth, and mortality; all four of these factors are expected to change with changes in climate. Productivity is likely to decrease in areas that are now or will become moisture limited; it is expected to increase (at least in the near term) in northern areas that are currently temperature limited (assuming moisture and nutrients are not limiting). An additional consideration with respect to the effects of climate change on productivity is that genotypes tend to be finely adapted to local climate. A change in the climate of an area may result in a situation in which local genotypes become maladapted to the new climate. New trees that become established at a site that are progenies of trees that have adapted to the area's historical climate may have reduced productivity under a new climate (or may not be able to exploit potential productivity gains). A potential management response could be to redistribute genotypes through seed transfers to better match genotypes to the future expected climate at particular sites. The implication is that in the case of renewed stands where productivity gains are possible, such gains may be contingent on a human management response in the form of seed or seedling transfers.

Composition, distribution, and structure of Canada's forest ecosystems

> *…climate change will result in changes in species composition and distribution, age-class distributions, and forest structure.*

Over time, climate change will result in changes in species composition and distribution, age-class distributions, and forest structure. These changes will occur gradually and they will be driven by several processes, including the following: physiological effects; the development of new conditions affecting relative competitive successes of plants that are native to an area; invasion of new species; differences in the abilities of individual species to acclimatize, adapt, or migrate; and changes in spatial and temporal patterns of disturbance. Forests will likely become younger over time and the frequency of early succession species and species adapted to disturbance (e.g., jack pine) will increase. Climatically suitable habitats for most species will move northward and will increase in elevation but the actual movement of species will lag behind the rate of movement of climatic niches. There are four main reasons that species change will not keep pace with change in climatically suitable habitats. First, the rate at which species can migrate is generally far lower than the rate at which new climatically suitable areas will develop. Second, even though a new species might be favored at a particular location under a new climate, the current species has the advantage of site occupation, resulting in a lag before the new species will be able to occupy the site. Third, species often do not function independently within an ecosystem. They require other species to conduct certain processes or provide certain functions or prepare the site in a certain way. Fourth, new climatically suitable areas may not be edaphically suitable (i.e., soil conditions may not be suitable).

White spruce and black spruce are important species in much of Canada's boreal forest. A number of studies suggest that these species may be affected negatively by climate change, resulting in a reduction in their net aerial coverage over time. Studies simulating the effects of climate change on jack pine have had mixed results. Jack pine responds favorably to increases in temperature and increases in spring precipitation but is negatively affected by increases in snowpack. Jack pine has adapted to forest fire and is successful on dry sites; it is likely to be favored by increases in fire disturbance and in areas that become warmer and drier. This potential spread of jack pine could, however, be counteracted by losses to the mountain pine beetle if the beetle spreads eastward into the boreal forest.

Regional forest vulnerabilities

The North

The boreal forest of the Yukon and the Northwest Territories comprises about 13% of Canada's total forest cover. Climate is expected to change much more significantly in the North than at southern latitudes. Significant impacts on northern forests are anticipated. The most significant impacts will occur as a result of northward movement of the tree line, increases in forest fire disturbance, and melting of large areas of permafrost (with negative consequences for the northern forest). The resulting changes in forests will have impacts on commercial forestry operations in the North, on subsistence activities, and on traditional and cultural values. For example, increases in wildfire activity may improve the supply of mushrooms but will also probably have negative impacts on woodland caribou.

British Columbia

British Columbia is both a coastal and a mountainous province. The province's climate varies widely and the terrain is diverse. British Columbia has the most productive and ecologically diverse forests of any province in Canada. The province is also Canada's largest producer of wood products. British Columbia was the first province to experience a major event related to climate change: the mountain pine beetle outbreak. The main sources of vulnerability to climate change for British Columbia's forests and forest sector over the next 50 years are as follows: restructured global markets with implications for British Columbia's exports, increased fire disturbance, increased losses from insect damage and disease, increased frequency and intensity of droughts in the southern interior portions of the province that are currently drought prone, species migration and changes in forest productivity, and loss of habitat in high-elevation forests.

Prairie provinces

The boreal forest is the dominant forest ecosystem in the Prairie province region. A significant portion of the western Canadian boreal forest could become exposed to drier climate, similar to that in the present aspen parkland zone. Forest fires are also expected to be more frequent, to be of higher intensity on average, and to burn over larger areas. Also, the fire season will become longer. Insect outbreaks are also expected to be more frequent and more severe. The combined effect of increases in forest fire, drought, and insect disturbances will lead to increased tree mortality, a younger forest, a shift toward pioneer tree species, and a loss of some forest areas. For example, over time, continuous forests at the southern boundary of the boreal forest will convert to aspen parkland and what is currently aspen parkland will convert to prairie grassland type ecosystems.

Ontario

One of the most significant sources of the vulnerability of Ontario forests to climate change is an increase in the frequency and intensity of disturbances. The overall area burned is projected to increase by between 50% and 300% by 2080, with most of the increase occurring in the remote northwestern portions of the province. Climate change is expected to result in increased spruce budworm damage in northern areas of the province and decreased budworm damage in southern areas. Warming will permit expansion of the northern range limit of many species; however, actual species migration will not keep pace with the rate at which climatically suitable niches expand. In the long term, species common to the temperate deciduous forest of southern Ontario (e.g., sugar maple, red maple, white pine) may migrate northward into what is currently boreal forest (subject to availability of edaphically suitable sites). However, such changes may take many hundreds of years. Thus, the only significant changes in tree species composition attributable to climate change in the near term will be changes in the relative abundances of species that are already present in particular areas. Climate change will favor disturbance-adapted species more than has been the case under Ontario's historical climate. This will likely contribute to an increase in the relative abundance of species such as jack pine, black spruce, white birch, and aspen. For areas that become drier, drought-tolerant species such as jack pine and aspen will be favored at the expense of species such as black spruce and balsam fir. In the Great Lakes – St. Lawrence forests there may be episodes of drought that lead to early stand dieback and breakup. In these ecosystems, xeric species (i.e., species adapted to dry conditions) such as red maple, white pine, and red oak will be favored over mesic species (i.e., species adapted to moist conditions) such as sugar maple and eastern hemlock.

Quebec

Three large forest ecozones comprise Quebec's forested landscape. From south to north, these are maple forest, fir forest, and spruce forest. Climatic zones for these ecozones are expected to move approximately 500 km to the north by 2050, which represents a rate of approximately 10 km annually. As noted, this rate is much higher than the fastest observed migration speeds of trees. Moreover, given the different methods and rates of dispersal among species and the differences in the physiological responses of species to changes in climate, species will migrate at different rates. This is likely to result in species assemblages that have previously not been experienced. Quebec's forests will also be modified by changes in disturbance. For example, the following changes in insect disturbance are anticipated: the range of the spruce budworm could increase significantly and outbreaks may last longer and cause greater defoliation; the range of gypsy moth may expand, threatening the hardwood forests of southern Quebec and urban forests; and the Asian long-horned beetle could expand its range into areas currently occupied by maples, elms, and poplars. In terms of forest fire, the frequency of wildfires is expected to increase in Quebec's western and northern regions, decrease in the east, and remain constant in the center of the province. The thinning of snow cover and early melt of snow cover are sources of concern for forest managers in southern Quebec forests. Soil exposed to open air exposes roots to freezing. Freezing at the root layer of trees in this region causes substantial root damage, which can significantly affect growth for a number of years.

Atlantic Canada

There are two major forest types in Atlantic Canada: the Acadian forest (which stretches across the Maritime provinces of Nova Scotia, New Brunswick, and Prince Edward Island), and the boreal forest (located in Newfoundland and Labrador). The distribution of native species in Atlantic Canada's forests is expected to shift with future climate change. Tree species that may have difficulty persisting under a changing climate may drop out (e.g., balsam fir), whereas those able to persist will dominate. Because tree-species migration is such a slow process, an influx of tree species common to the Carolinian forest of the northeastern United States is unlikely to occur during the 21st century unless assisted through planting programs. Insects are a primary cause of disturbance to both the Acadian and the boreal forests of Atlantic Canada. Spruce budworm in particular represents a significant source of forest disturbance. Other species that will contribute to the vulnerability of Atlantic Canadian forests in the future include the spruce beetle and the hemlock woolly adelgid. The former is an opportunistic native species that takes advantage of windthrown trees. The latter species, currently excluded from Atlantic Canada by winter temperatures, may capitalize on moderate winters and could alter the composition of Atlantic Canadian forests by killing the eastern hemlock component of Acadian forests as it has done in the United States. Given the mild and wet conditions prevalent in Atlantic Canada, drought is considered a comparatively minor force of disturbance. Less than 1% of the total forested area of the Atlantic Canadian provinces was burned in 2005. Given the current direct contribution of fire to the overall disturbance regime of Atlantic Canada and the overall wetter conditions predicted for the region in a future climate, fire itself will not likely become a matter of increased concern. Acadian forests are, however, subject to damage by wind. Wind is also a major disturbance regime in the forests of Labrador and on the island of Newfoundland. The predicted warming of the north Atlantic may result in an increase in the severity and frequency of severe weather. Atlantic Canadian forests will therefore become vulnerable to large-scale windthrow, especially in coastal regions.

Impacts on the forest sector

Forest management

Most (94%) of the forest land in Canada is under public ownership. Timber supply on public forest lands is generally described by measures such as the allowable annual cut and the long-run sustainable yield. Climate change has implications for both current and future timber supply. The net impact of climate change on timber supply will be determined by how climate affects a number of interrelated factors, including the impacts of climate change on forest land area, growth rate, disturbance patterns, management inputs, regulatory constraints, regeneration success, and species composition. At local scales, changes in timber supply may be positive or negative, depending on location, time frame, and human adaptation to the effects of climate change. It is not possible at this time to estimate the impacts of climate change on timber supply nationally. It merits noting, however, that the national softwood allowable annual cut from provincial public lands in 2004 was around 159 million m^3 whereas the actual harvest of softwood fiber was between 140 and 150 million m^3. Thus, any significant reductions in softwood allowable annual cut would likely translate into reductions in harvest with associated reductions in production, exports, incomes, taxes, and employment.

Climate change may also have an impact on Canada's ability to achieve objectives for sustainable forest management. The Canadian Council of Forest Ministers has developed a framework that defines sustainable forest management and provides a basis for measuring progress toward it. The framework is based on six criteria. The criteria represent important classes of values that Canadian society associates with forests and forest management: biological diversity, ecosystem condition and productivity, soil and water, role of forests in global ecological cycles, economic and social benefits, and society's responsibility. The framework also includes a set of indicators or measures that assess Canada's performance in providing a socially desired level of benefits for each criterion. Climate change, which is beyond the control of the Canadian forest management sector, has the potential to negatively affect each of these classes of values and many of the measures that are currently used to measure Canada's performance in sustainable forest management.

Forest operations

A significant portion of the harvest in Canada occurs in the winter when the ground is frozen. Harvesting on frozen ground allows for access to wetlands, reduces delivered wood costs, and reduces soil disturbance. On the basis of projections for warmer winters and more precipitation in the future, the time window when frozen-ground conditions exist will shorten. This is a potentially large problem in many boreal forest regions, because some forest management agreement areas can consist of up to 40% wetlands. Forest companies have few options to deal with the decrease in frozen-ground conditions. In the short term, more harvesting can be done on summer ground, but eventually timber supply in summer-access areas will run out. Some have suggested building more permanent roads, but these are expensive. In addition, the current provincial forest management policy in many jurisdictions is to minimize permanent road construction and to rehabilitate temporary roads once harvest activities are complete. Specialized equipment (e.g., high-flotation tires) is available but it is expensive and can only be used for a short time each year. In addition, some of these technologies require additional maintenance. This also adds to costs.

Forest industry

In addition to being potentially affected by changes in timber supply and changes in delivered wood costs, the Canadian forest industry will potentially be affected by changes in global markets resulting from climate change. Canada is the world's leading exporter of forest products. Research shows that climate change will increase global timber supply. Some countries will gain more than others and this will lead to shifts in the comparative advantages of exporting countries. Climate change is expected to reduce the economic benefits of the trade in forest products for North American producers. This reduction is expected to be significant in the early part of the century, as a result of a decline in relative prices and in relative market share by North American producers.

Forest-based communities

The impacts of climate change will probably not be evenly distributed across Canadian society. Some segments of Canadian society are relatively more vulnerable because of their location, their strong association with climate-sensitive environments, or their particular economic, political, and cultural characteristics. Rural, resource-based communities are of particular concern. Forest-based communities face the same kinds of impacts and risks associated with climate change that non-forest-based communities face.

These include potential health effects (e.g., heat stress, effects on air and water quality, increased exposure to insects and diseases), impacts on infrastructure (e.g., roads, sewers, building heating and cooling needs), and exposure to extreme weather events (e.g., floods and storms). However, forest-based communities face a number of additional risks that will magnify their vulnerability to climate change. First, residents of forest-based communities have strong ties to the surrounding climate-sensitive forest landscape. Second, residents in forest-based communities (particularly communities that closely interface with a surrounding forest) face increased risks owing to expected increases in wildfire activity in some locations. Third, changes in wood supply or in the relative competitiveness of local firms can have significant impacts on local economies, particularly in cases in which those economies are heavily dependent on the forest-products sector. Additional socioeconomic factors that contribute to the heightened levels of vulnerability of Canadian forest-based communities include the following:

- The potential for lower adaptive capacity (e.g., small and undiversified economies and overspecialized local labor forces with skill sets that are not transferable to other sectors),
- the potential for larger scale institutional responses to environmental issues and climate change that are targeted to our increasingly urban society and that ultimately affect smaller rural communities or reduce their capacity to adapt,
- a lack of consideration of climate change in forest management decisions and forestry institutions that may ultimately lead to higher impacts manifesting at the community level, and
- the potential for misperception of the risks of climate change.

Forest-based public and common-property goods and services

Climate change will affect a range of environmental goods and services associated with forests. These goods and services include clean air and water, productive soils, wildlife, protection and preservation of biodiversity, existence value (i.e., the knowledge that certain species or ecosystems continue to exist), bequest value (i.e., the knowledge that we are preserving natural capital for future generations), the provision of aesthetically pleasing vistas, and the provision of outdoor recreation opportunities. For example, there are concerns about the impacts of climate change on endangered species such as woodland caribou.

Recommendations and conclusion

The magnitudes of change in climate that will be faced by Canada's forests and forest sector and the consequent scale of expected impacts have no historical analogue. Canada's forest sector will need to adapt and it will need to do so without the benefit of prior experience. Forest managers can expect the unexpected and they can expect that change will be ongoing and unrelenting. Adapting forest management to climate change is starting to be recognized as a necessity. Adaptation leads to a number of benefits, including exploiting opportunities and maximizing potential benefits, reducing potential negative impacts, and reducing risks. There are a number of examples in Canadian forestry that show that the process of adaptation has already begun. A few companies are investigating how to incorporate climate change into their long-term forest management planning. A few provincial forest management agencies are beginning to consider their adaptation requirements. These are, however, preliminary steps and much more needs to be done to prepare for and adapt to future climate change. Although there is growing recognition of the need to adapt to climate change, there remains some degree of uncertainty about where and how to adapt. A useful first step would be to identify and better understand sources of vulnerability in forest ecosystems and the forest management system.

Even after sources of vulnerability have been documented, unexpected impacts will probably be experienced. Thus, in addition to the development of specific adaptation measures, there is also a need to enhance the general capacity of forest managers and forest management to adapt. Not only would this be of value with respect to climate change but also it would position the forest sector to address the full array of global, social, political, and economic changes that it faces. According to Smit and Pilosova (2001), core attributes of systems with high adaptive capacity include an awareness of and an understanding of the urgency of the issue; a strong science capacity and access to technological options for adaptation; financial resources; effective institutions that are forward looking, flexible, and self-adaptive and that provide the authority for local adaptation to occur; high levels of human capital; effective networks and high levels of trust between various vested interests to facilitate information sharing and the development of collaborative solutions; and mechanisms for knowledge generation and dissemination and for the creation of tools and databases.

Recommendations

1. Enhance the capacity to undertake integrated assessment of vulnerabilities to climate change at various scales

Integrated assessments of vulnerabilities to climate change are required at multiple spatial and temporal scales and for various types of human systems. For example, an understanding of system vulnerabilities is required at national, regional, and local scales. Methods and approaches are required that consider the vulnerabilities of different types of human systems to climate change, including forest management systems, protected areas, and forest-based communities.

2. Increase resources for impacts and adaptation science and also increase resources to monitor the impacts of climate change.

Climate change is a reality and it has major implications for the future state of forests. Foresters rely on prediction models (e.g., growth and yield and timber supply) to manage forests to achieve social objectives for public forests. In the past, historical data was used in estimating prediction models. This is no longer valid. Historical conditions are not representative of future conditions. Decisions made today that are based on expectations that future conditions will match historical conditions will likely fail. Thus, our success at managing forests depends on our ability to predict the future impacts of climate change on forests. However, the difficulty that forest managers face is that although climate change produces a greater need to predict the future (under changing conditions), it also produces greater uncertainty surrounding predictions of the future. Increased resources for monitoring the impacts of climate change and for impacts and adaptation research can reduce this uncertainty. More reliable prediction methods, lower uncertainty regarding predictions, and the ability to provide projections at scales relevant to decision-makers will be essential if we are to develop efficient and effective strategies for adapting to climate change.

3. Review forest policies, forest planning, forest management approaches, and institutions to assess our ability to achieve social objectives under climate change

The Canadian forest sector has been hesitant to incorporate climate change into policy and planning. This may in part be due to the high levels of uncertainty that are associated with the future impacts of climate change, especially at the stand and forest levels. Nevertheless, forest companies are already beginning to experience some impacts that may be related to climate change (e.g., a shorter winter-harvest season and the expansion of the mountain pine beetle's range). Moreover, the long growth cycles of trees puts forest management in a unique position in terms of the need to include climate change considerations in current planning and decision-making. Thus, consideration of climate change is not something that should be deferred in the forest sector.

There are a number of areas in which future climate change has important implications for current forest management. There is a need to:

- incorporate climate change into growth and yield forecasts.
- incorporate climate change into long-term timber supply analysis and forest management planning.
- incorporate climate change into reforestation choices.
- consider climate change in identifying protection program requirements and in specific types of adaptations, such as reducing vulnerability by managing landscape configurations (e.g., "fire-smart" landscapes, insect-proofed landscapes).
- incorporate climate change considerations into sustainable forest management objectives and into the practices that forest managers use or may use to achieve modified objectives.

A cumulative effects approach may, in some cases, be needed to determine appropriate actions. For example, some areas will be subject to increased risk of both drought and fire and therefore a shift in species composition toward more jack pine could provide multiple benefits.

4. Embed principles of risk management and adaptive management into forest management

Climate change will increase the risk and uncertainty associated with forest management objectives. A change in risk may have implications for forest values and for choices made. It can be argued that the current approach to forest management is prescriptive and deterministic. A prescriptive and deterministic approach that is based on historical experience may be satisfactory when conditions are stable but this approach has somewhat less applicability when conditions could change in multiple possible future directions.

Increased timber supply risk resulting from climate change has the potential to have real economic impacts and also to influence optimal harvest plans. Accounting for and managing risk will be an important adaptation to climate change. Risk management strategies include risk prevention, risk reduction, risk spreading (e.g., insurance schemes), and portfolio diversification.

In addition to the need to manage risk, there is a need to be better prepared to deal with unanticipated and unpredictable events. The mountain pine beetle event, for example, was not anticipated and not predicted. Functional diversity, flexibility, management systems that recognize and account for uncertainty and unpredictability, and social structures that encourage adaptive management are important features in systems that are vulnerable to unpredicted and unanticipated events.

5. Maintain or improve the capacity for communications, networking, and information sharing with the Canadian public and within the forest sector

Improving communications, networking, information sharing, collaboration, and cooperation is one way to effectively address the many challenges faced under a changing climate. Social capital is essentially the degree to which elements of a social system are networked and the degree to which constituents of the social system trust each other. Social capital provides individuals and groups with information and resources to which they might not otherwise have access. It contributes to resiliency and adaptive capacity.

Conclusion

The purpose of this report is to raise awareness about climate change, its impacts on Canada's forest sector, and its implications for forest management and the forest sector in Canada. Canada's forest sector is experiencing and will continue to experience the impacts of rapid climate change. This has important implications for Canada's ability to manage forests in an economically and environmentally sustainable fashion. Ultimately, forest managers will need to adapt. The information presented in this report should help to inform the forest management community and contribute to a more constructive debate about adaptation requirements.

One strong finding is that we face significant levels of uncertainty regarding the impacts of future climate change. Uncertainty should not be a barrier or prevent adaptation, but it does make adaptation somewhat more challenging. Science can help to reduce this uncertainty over time. Climate change is fundamentally a scientific issue with very significant potential socioeconomic impacts and important policy implications. A stronger, better funded, and more focused science-based research effort will be required. However, this scientific effort cannot and should not proceed independently of the needs of policy-makers and forest managers. Mechanisms must be put in place to directly link science to policy, planning, and decision making.

CHAPTER 1

INTRODUCTION

Climate changes naturally over time in response to changes in the earth's orbit, changes in solar activity, volcanic activity, and changes in the composition of the atmosphere (Girardin et al. 2006). Most of these factors, however, result in climate changes occurring over long time periods. The rate of climate change over the last 100 years cannot be explained by natural factors. According to the Intergovernmental Panel on Climate Change (IPCC), anthropogenic change in the composition of the atmosphere is the main factor contributing to recent rapid climate change and will be the principal factor forcing climate change over the next 100 years (IPCC 2007).

The IPCC's *Fourth Assessment Report* (IPCC 2007) confirms earlier assessments that climate change resulting from the actions of humans is real and significant. The IPCC states in this report that warming over the last 100 years is "unequivocal," with an estimated 0.74 °C (±0.18 °C)increase in mean global temperature during the period 1906–2005. The report also provides best estimates of projected increases in temperature for the 2090s (compared with the period 1980–1999) ranging from 1.8 °C, assuming the most optimistic scenario of future greenhouse gas emissions, to 4.0 °C if emissions were to increase under the worst-case scenario. For Canada, particularly in the midcontinental regions, the general circulation models typically project a level of warming that is greater than the global average (Kirschbaum and Fishlin 1996; Weber and Flannigan 1997).

Forests are sensitive to climate. Present-day latitudinal and elevation differences in temperature, precipitation, wind, and radiation explain much of the large-scale spatial variation in species composition and productivity of forest ecosystems (Iverson and Prasad 1998; Aber et al. 2001; Hansen et al. 2001; Jackson 2004). Climate has a direct influence on biological and ecological processes. Climate affects regeneration, phenology, synchrony in phenology of interacting species, photosynthesis, respiration, water uptake and transpiration, disturbances (i.e., fire, insects, diseases, storms, and drought), the competitive success of particular species, and the rates of accumulation and decomposition of dead organic material. Before the onset of significant anthropogenic greenhouse gas emissions, changes in climate were generally slow enough to allow long-lived tree species to acclimatize, adapt, or migrate. Since then, the "climatic envelopes" in which Canada's diverse forest ecosystems developed have begun to shift at unprecedented rates. The implications of a rapidly warming climate for long-lived organisms (such as trees) and for human management systems with long planning horizons (such as forestry) are significant (Dale et al. 2000; McNulty and Aber 2001; Chuine et al. 2004).

Concern is growing about the impacts of climate change in the forest sector and the need for adaptation (e.g., see Standing Senate Committee on Agriculture and Forestry 2003; Lazar 2005; Snetsinger 2006; Lemprière et al. 2008). The Canadian Council of Forest Ministers (CCFM) has identified climate-change mitigation and adaptation along with transformation of the forest sector as "two priorities of national importance" for Canada's forest sector (CCFM 2008). Canada is in a uniquely vulnerable position relative to other countries because of the expected magnitude of climate change, the sensitivity of forests to climate change, the long growing cycles of trees, and the socioeconomic importance to Canadians of forests and the forest sector. Early action, however, has the potential to reduce our vulnerability to climate change. Adaptation may reduce the current negative impacts of climate change and may maximize the benefits from climate change. Moreover, given that forestry investments mature over long time frames and are generally irreversible, early adaptation is needed to minimize long-term future negative impacts of climate change. Therefore, it is important that foresters are aware of climate change and begin to identify and incorporate adaptation strategies and approaches in policy, management decisions, and long-term plans.

This report complements and updates previous synthesis documents on the impacts of climate change on Canada's forests (e.g., Saporta et al. 1998; Forget et al. 2003; Lemmen and Warren 2004; Juday et al. 2005; Johnston et al. 2006; Lemprière et al. 2008). The report is based on forestry author contributions to the recent Canadian national assessment report on climate change impacts (Lemmen et al. 2008). The purpose of the report is to raise awareness about climate change and to provide information to forest managers to assist them in beginning to identify and assess adaptation requirements and options. The report provides a summary of changes and events that have occurred in Canadian forestry over the last 30 years that may be at least partially related to recent climatic trends. It then describes how future climate change might affect forests and the forest sector both in general terms and in various regions throughout Canada. The potential implications of climate change for forest management, forestry operations, the forest industry, and forest-based communities are considered. Finally, adaptation challenges, considerations, and options are discussed and recommendations are provided.

CHAPTER 2

CURRENT IMPACTS ON CANADA'S FORESTS

Climate change is already affecting Canada's forests (Lemmen et al. 2008). This chapter describes recent changes in Canadian forests that are related in some way to recent climate change. The most visible effects of climate change in the Canadian forest sector over the last 30 years are in the form of changes in the frequency, severity, or geographic location of disturbances (see figure 1). However, changes in the length of the growing season, tree lines, and phenology are also being observed. The examples discussed in this chapter were chosen because they provide evidence that climate change is having an impact now. Moreover, the kinds of climate change and impacts that are currently being observed may be precursors of even more significant events in the future as our climate continues to warm at a potentially accelerating rate.

Observed changes in growing season, phenology, and tree lines

Climate change is increasing the length of the growing season. Zhou et al. (2001) found that the average length of the growing season (expressed as period of vegetation greenness) increased 12 days in North America and 18 days in northern Eurasia between 1981 and 1999. Similarly, McDonald et al. (2004) found that the mean date of spring thaw in North American boreal forest ecosystems advanced by 13 days between 1988 and 2001; Goetz et al. (2005) reported similar patterns in tundra regions of Canada and Alaska.

Trees are starting to respond to climate change. Bernier and Houle (2005) noted that bud burst for sugar maples is occurring several days earlier than it did a hundred years ago and Colombo (1998) reported similar results for white spruce in Ontario. Beaubien and Freeland (2000) reported that the flowering period for aspen poplar is now occurring 26 days earlier than it did in the last century. Danby and Hik (2007) found that tree lines have expanded upward in elevation and stand densities have increased in the Yukon as a result of warming during the 20th century. Roland and Matter (2007) also noted that the tree line is increasing in elevation. The result is encroachment on alpine ecosystems. Soja et al. (2007) described a similar result for Siberia. Gamache and Payette (2004) reported that black spruce trees have been growing taller in the northern forest–tundra of eastern Canada since 1970.

The 2001–2003 drought

A specific event that may be tied to recent climate change is the nationwide drought in 2001–2003. Droughts are normal in Canada: for example, significant droughts occurred in the early 1930s, 1961, and 1988 and most recently in 2001–2003 (Wheaton 2005). However, the 2001–2003 drought was unprecedented in terms of length, aerial extent, and (in some locations) severity (Wheaton 2005). This drought was not restricted to Canada. For example, Zeng et al. (2005) and Lotsch et al. (2005) described a drought event that occurred over mid-latitude regions across the northern hemisphere from 1998 to 2002.

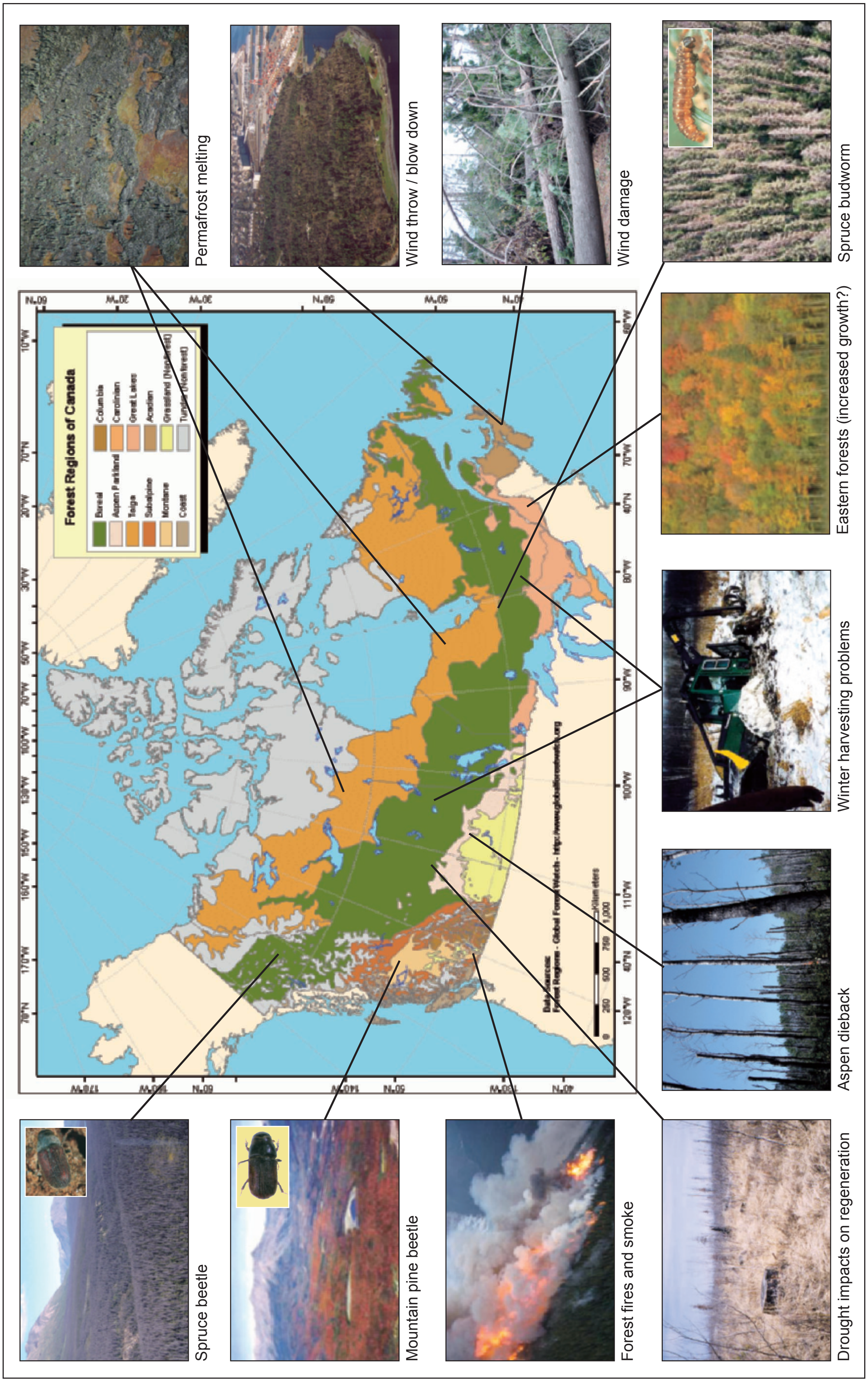

Figure 1. Regional impacts of climate change on Canada's forests.

Aspen dieback started to be observed in the early 1990s (Hogg et al. 2002). On the basis of aerial surveys conducted in 2004, Hogg et al. (2005) noted that the 2001–2003 drought may have contributed to widespread mortality of aspen trees in western Saskatchewan and eastern Alberta. This was confirmed in a paper by Hogg et al. (2007) that finds that aspen forests in the western Canadian interior forests are moisture limited and that the recent drought contributed to increased stem mortality and growth decreases in these forests.

Drought may also have secondary affects. For example, the devastating fire seasons in British Columbia and the Yukon in recent years are likely due to a combination of increased fuels (the result of mortality caused by insect infestation) and the hot, dry conditions that are associated with drought. Drought increases tree stress and the susceptibility of trees to diseases and parasites (Dale et al. 2001). For example, Juday and colleagues (2005) cited drought as a potential factor contributing to increased mortality caused by the spruce bark beetle in the spruce forests of Alaska's southern peninsula.

Increased forest fire activity

Fire activity in a specific region during a particular year is related to the weather in the current and previous years, atmospheric conditions, lightning activity, ocean currents (i.e., El Nino and La Nina), the availability of fuels (i.e., forest vegetation characteristics), decomposition rates (which affect fuel accumulation), land-use activities, topography and terrain features, and fire management (Flannigan et al. 2001; Podur et al. 2002). These factors are interrelated and they are in some cases stochastic (e.g., weather). Thus, the level of fire activity in a particular area can vary widely from year to year.

One example of how recent climate change is affecting fire activity is that extreme fire seasons are occurring more frequently and it is becoming more commonplace for severe burning conditions to occur at times of year when they typically do not occur. For example, the 2003 fire season in British Columbia was worse than any previous fire season in the province's history. The total cost of fire fighting was estimated at $700 million (Filmon 2004). Over 334 homes and businesses were destroyed, and over 45 000 people were forced to evacuate their residences (Filmon 2004). Similar abnormal fire activity has occurred in other parts of Canada. The summer of 2004 was the warmest on record in the Yukon. The Yukon also experienced below normal precipitation and a record number of lightning strikes in that summer. These conditions combined to produce a record fire season in the Yukon; approximately 1.8 million hectares burned. The previous record (in 1958) was less than half this area: 891 000 hectares. Abnormal fire weather conditions have also been observed in eastern Canada. For example, extreme fire weather conditions existed in northwestern Ontario as late as September 2006. Fire suppression operations are also beginning to gear up much earlier in the season than in previous years.

…extreme fire seasons are occurring more frequently…

The assessment of trends in forest fire activity is complicated by poor data from the early part of the 20th century (i.e., the area burned was probably underestimated before 1960 [Amiro et al. 2004]) and the highly variable nature of forest fire activity from year to year. Nevertheless, fire researchers have established that forest fire activity has increased significantly over the last 40 years (Flannigan and Van Wagner 1991; Podur et al. 2002; Stocks et al. 2002; Gillett et al. 2004; Amiro et al. 2004; Juday et al. 2005; Soja et al. 2007).

Kasischke and Turetsky (2006) reported that despite concurrent increases in suppression capacity, the frequency of large fire years and the area burned in the North American boreal region (i.e., Alaska and Canada) doubled between the 1960s–1970s and the 1980s–1990s. Most of these increases occurred in the western part of the boreal forest region. In addition, the proportion of the total area burned at the beginning and end of the fire season is increasing, suggesting that there has been a general lengthening of the time period when forests are susceptible to forest fire.

Flannigan and Harrington (1988), Gillett et al. (2004), and McCoy and Burn (2005) noted that although many factors influence fire activity, temperature is one of the strongest predictors of area burned. Westerling et al. (2006) discussed the linkage between global warming and forest fire activity in the western United States. They found that snowpacks are melting 1–4 weeks earlier then they did 50 years ago, summer temperatures are higher, the fire season has increased by 78 days, and the average burn duration of fires has increased from 7.5 days to 37.1 days. These changes have resulted in a 4-fold increase in the frequency of large fires and a 6-fold increase in area burned in the western United States.

Although there is evidence that climate change has contributed to increased fire activity over the last 40 years, there is a need for some qualification and historical context. First, in addition to varying over time, forest fire activity varies by region. In general, the fire cycle (i.e., average number of years between stand-replacing fires) is longer in eastern portions of the boreal forest than in western portions (Bergeron et al. 2006). Second, although forest fire activity has increased in recent years, fire activity in the early part of the 20th century may have been much lower than in the 19th century (Bergeron and Flannigan 1995; Bergeron et al. 2004, 2006; Girardin et al. 2006).

Mountain pine beetle

The mountain pine beetle is native to North America. The primary host of the mountain pine beetle is mature lodgepole pine but this pest does attack other species of pine, including Ponderosa pine and jack pine (Cerezke 1995; Carroll et al. 2004). Beetles feed on live phloem tissue under the bark, eventually killing the tree through girdling. They also carry the blue stain fungus. This fungus spreads through a tree's sapwood and eventually stops the movement of water from the roots to the crown.

The mountain pine beetle is normally an innocuous forest pest. However, outbreaks occasionally occur that result in widespread pine mortality over large areas. There have been four major outbreaks of mountain pine beetle in British Columbia over the last 120 years (Taylor et al. 2006; Carroll 2006). The current outbreak is by far the most widespread. As of 2005 over 8.7 million hectares of pine forest in British Columbia were affected (BC Ministry of Forests and Range 2006). This area is 10 times larger than that affected by any of the previous infestations (Carroll 2006). Moreover, the regions currently being affected have never previously been exposed to mountain pine beetle attacks. To date the beetle has killed about 40% of the province's inventory of mature lodgepole pine (Walton et al. 2007). Projections suggest that the infestation could result in the loss of 77% of the province's mature pine by 2014 (Walton et al. 2007). The mountain pine beetle has recently spread from British Columbia into regions of northwestern Alberta that have never before been infested. Significant populations have become established in areas around Grande Cache and Grande Prairie and on the border of Alberta and British Columbia west of Peace River.

Two factors have contributed to the current outbreak: the presence of large areas of mature lodgepole pine, and an unprecedented number of abnormally warm winters in consecutive years (Carroll et al. 2004). Previously, the geographic range of the mountain pine beetle was limited by climate. Recent changes in British Columbia's climate have resulted in a greater than 75% increase in climatically optimal beetle habitat (Carroll et al. 2004). The impacts on timber supply and consequently on British Columbia's forest economy and forest-based communities are significant (see Chapter 5 on impacts on the forest sector).

Spruce bark beetle

The Yukon is currently experiencing the largest outbreak of spruce bark beetle ever recorded. Although the beetle is endemic to the area, population levels have traditionally been low, the area infested has been small and impacts have been limited. Historically, the main factors limiting beetle distribution were cool, wet summers and cold winters. The beetle required two full years to complete its life cycle because the summers were cool. Consecutive cold winters generally resulted in beetle mortality and reduced populations (Juday et al. 2005; Berg et al. 2006). The scale of the current outbreak is unprecedented. Forests covering over 340 000 hectares in southwest Yukon have been affected (<http://yukon.taiga.net/swyukon/beetle.cfm> accessed 5 March 2007) and there has been some tree mortality in 1.6 million hectares in Alaska because of this outbreak as well (Juday et al. 2005). The primary host of the beetle is mature spruce (i.e., Sitka spruce, white spruce, and hybrids). The current outbreak is directly related to the recent drought and the unprecedented warm summer and winter conditions in the Yukon and Alaska (Berg et al. 2006; Soja et al. 2007). Beetle populations are beginning to decline in Alaska, primarily because of reduced availability of live host trees.

Dothistroma needle blight

The mountain pine beetle infestation, the spruce bark beetle outbreak, and the increase in forest fire activity are three disturbances related to climate change that are occurring over relatively large spatial scales. Other equally unprecedented impacts of recent climate change on forests are occurring at smaller scales. Dothistroma needle blight is a fungus that attacks the foliage of lodgepole pine and other pine species (Woods et al. 2005). The fungus normally has a minor impact on forests. However, it has recently become an epidemic in northwestern British Columbia, attacking both young lodgepole pine plantations and mature lodgepole pine forests. It is causing extensive mortality in lodgepole pine plantations and some mortality in mature pine (the damage in mature pine is unprecedented). Woods et al. (2005) conducted aerial surveys from 2002 to 2004. Of the 41 000 hectares they surveyed, 92% were infected. Nine percent of the area will need to be replanted because of pine plantation failure, and 7% of the area has trees that have been killed by the needle blight (Woods et al. 2005). Host availability and changes in environmental conditions that favor the pathogen are the main factors contributing to the increase in damage caused by dothistroma needle blight. The

> *Other equally unprecedented impacts of recent climate change on forests are occurring at smaller scales.*

environmental change associated with the outbreak is an increase in the frequency of warm rain events during the summer compared with the mid-1990s (Woods et al. 2005); this may be due to recent climate change.

Implications

The examples in this chapter show that climate change is already affecting Canada's forests and they illustrate two general characteristics of the impacts of climate change. First, events such as the mountain pine beetle infestation are often the result of a number of interacting factors. Changes in local climate may contribute to the event, but many other factors (e.g., characteristics of specific disturbance agents, interactions between disturbances, tree and forest-ecosystem characteristics, and previous management) may also combine to create a set of circumstances that lead to a particular event or impact. This underscores the multifaceted nature of the assessment of the impacts of climate change and the many challenges that we face in predicting impacts resulting from complex interactions. It also illustrates that it is possible to reduce the sensitivity of forests to climate change by managing the landscape.

A second feature of climate change that is illustrated by recent experiences is that it has the potential to result in multiple, interacting impacts that occur simultaneously. Changes in drought risk, fire risk, risk of insect and disease disturbance, growth and yield, and extreme weather risk will all occur at the same time. This has important implications for forest management. First, forest managers will need to recognize, understand, and adapt to the cumulative impacts of climate change. Assessment frameworks and adaptation strategies that are comprehensive, holistic, and integrated are required. There is also the potential that the significant complexities of the risks associated with climate change could result in under- or over-estimation of risk by decision-makers (Davidson et al. 2003). Surveys of forest managers in British Columbia and Ontario found that forest managers felt that the impacts of climate change on forest ecosystems were not well understood by the public or the forest-management community (Ogden and Innes 2007a; Colombo 2006; Williamson et al. 2005). There is, therefore, a need for education, communication, generation of new databases and tools that can be used by and will be useful to forest managers; these initiatives will improve and enhance our basic scientific understanding of the impacts of climate change. However, because the results of climate change are multidimensional, the research that is undertaken and the knowledge and tools that are produced by scientists will need to be multidisciplinary, holistic, and integrated.

Climate change has the potential to result in multiple, interacting impacts that occur simultaneously.

CHAPTER 3

FUTURE IMPACTS ON CANADA'S FORESTS

The impacts described in the previous chapter illustrate that forests are sensitive to rapid climate change. An understanding of the current impacts of climate change provides a basis for understanding how future climate change may affect Canada's forests. Canada's climate will continue to warm into the next century. The IPCC reports best-estimate global temperature increases of 1.8 °C (in the IPCC's B1 scenario, which is its lowest emissions scenario) to 4.0 °C (in the IPCC's A1F1 scenario, which is a fossil-fuel-intensive scenario) by 2100 (IPCC 2007). Warming trends will be significantly more pronounced at northern latitudes (Lemmen et al. 2008). The rate of future warming experienced by Canada's forests will be significantly higher than what was experienced in the last 100 years in Canada and also significantly higher than the rate of increase in global average temperature over the next 100 years.

This chapter provides an overview of expected future impacts of climate change on Canada's forests. However, the inter- and intra-relatedness of the site, disturbance, and physiological factors that contribute to the final impacts of climate change and the large number of these factors make it difficult to systematically describe impacts in a straightforward and integrated way. Climate change will have primary, secondary, and tertiary effects on forest ecosystems. The many interactions and feedbacks between these effects make the story complex. Nevertheless, it is possible to identify drivers of change on forests, interactions between these drivers, and some of the overriding variables that will ultimately affect or determine the scale of impacts on forests (Figure 2). The remainder of this chapter discusses many of the items identified in Figure 2: the drivers of change (i.e., the items identified in the three boxes on the left side of Figure 2) and then the potential impacts on forests (i.e., the items within the box on the right side of Figure 2).

Given what we are already seeing in forests, we can predict that changes in disturbance regimes will be one of the key ways by which climate change will affect forests in the future. The potential effects of future climate change on extreme weather, forest fires, insects, and disease will be summarized in this chapter. However, climate change will also affect resources required by trees (i.e., moisture, nutrients, heat units), site conditions, and biological processes in individual organisms. These changes will have implications for growth, mortality, and regeneration; they will also put pressure on trees to acclimatize, adapt, or migrate. The ways in which climate change will affect biological processes, productivity, and the composition and structure of forests will be discussed later in this chapter. Next, forest zones will be identified where the factors described in the previous chapters combine in such a way that these zones will be particularly sensitive and vulnerable to climate change. This will be followed by a review of the literature on the impacts of climate change on Canada's boreal forest. The chapter concludes with a description of sources of uncertainty in predicting future impacts.

Extreme weather and climatic variability

An increase in risk associated with increases in the frequency and intensity of extreme weather and climatic events was identified by the IPCC as one of five key categories of reasons for concern about future climate change (Smith et al. 2001). (The other four categories are risk to unique ecosystems, distribution of impacts, aggregate impacts, and

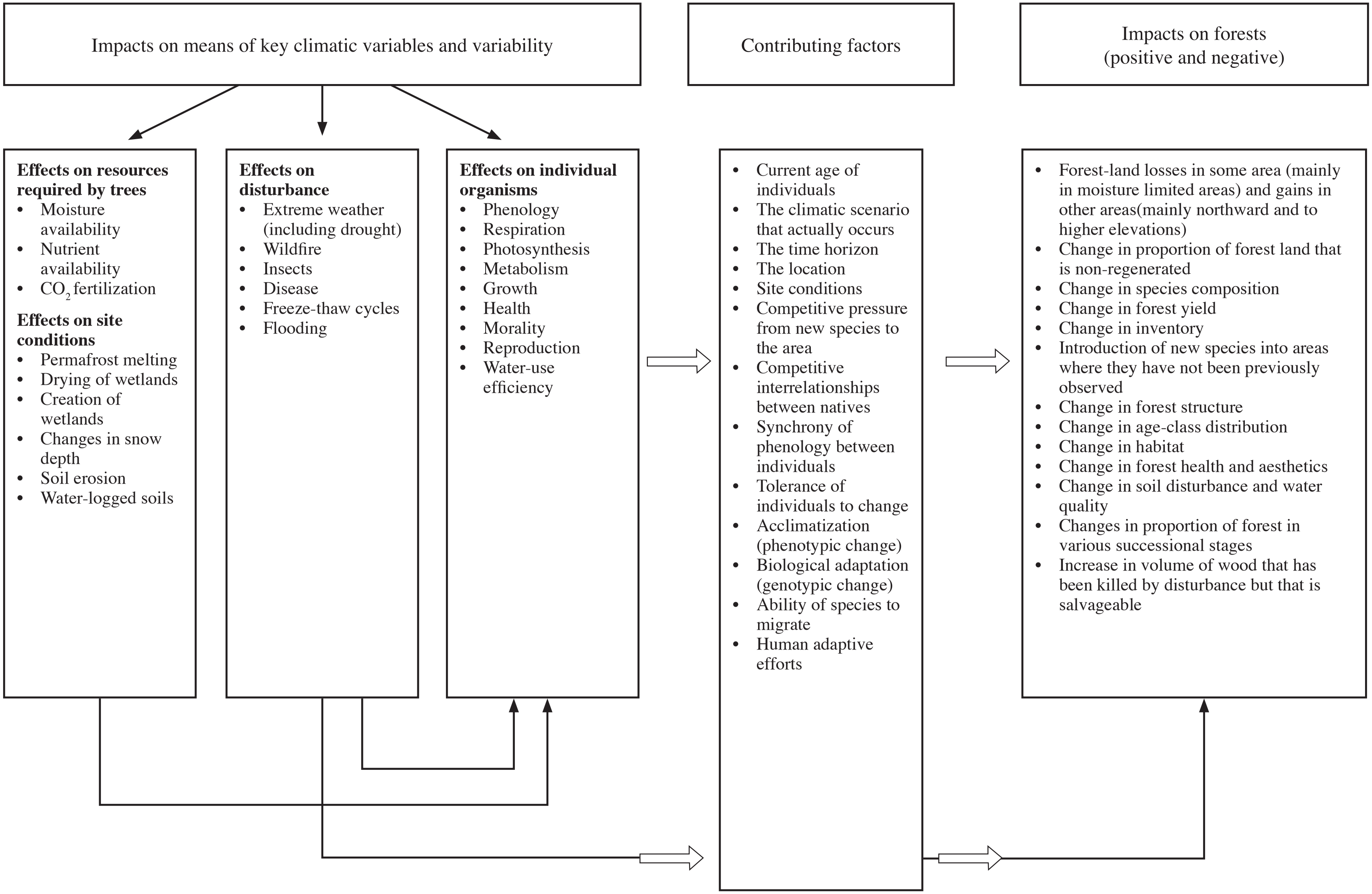

Figure 2. A map of climate change impacts on forests.

risk from large-scale discontinuities.) Mastrandea and Schneider (2004) suggested that a slightly higher than 2 °C increase in average temperature may result in "large increases" in the risk of extreme weather and climate. Under a worst case climatic scenario, a 2 °C increase in Canada's average temperature is possible as early as 2030 (see Figure SPM.6 in IPCC 2007).

It seems probable that a warmer atmosphere (i.e., containing more stored heat energy) will generate increased frequencies and intensities of extreme events both in weather (e.g., storms) and climate (e.g., droughts) (Berz 1993; Meehl et al. 2000; Easterling et al. 2000; Smit et al. 2000; Smit and Pilosova 2002). Examples of extreme phenomena likely to increase in a warmer climate include thunderstorms and windstorms, hailstorms, intense precipitation events leading to flooding, tornadoes, hurricanes (and tropical storms), abnormally warm winters, and periods of hot, dry weather (leading to extreme forest fire conditions, extended fire seasons, heat waves, and droughts lasting months or even years).

Graumlich (1993) and Parmesan et al. (2000) suggested that extreme weather and climatic variability (and patterns of disturbance related to extreme weather and climatic variability) affect growth and species morphology and is a factor explaining stand composition and structure. Changes in extreme weather, climatic variability, and related disturbance patterns are likely to affect terrestrial biota in a number of ways: they may force organisms to change their reproduction strategies, they may favor species that are better adapted to increased climatic variability and disturbance, they may affect population and community dynamics, and they may alter ecosystem processes.

Drought is an extreme climatic event. As noted earlier, droughts do occur in forested areas in Canada and they affect forested ecosystems (Hogg and Bernier 2005).The degree to which a drought affects a particular forest depends on the soils, species, and plant age in the forest and on the duration and severity of the drought (Dale et al. 2001). Plantations, shallow-rooted trees, drought-intolerant trees, trees growing on soils with a low capacity to hold water (Spittlehouse 2003), and trees growing in areas that are already moisture limited are particularly vulnerable. However, if a drought is long and severe enough, most of Canada's indigenous tree species are vulnerable.

It is anticipated that continued global warming will increase the length, frequency, and severity of drought events (Dale et al. 2001; Sauchyn et al. 2003). Moisture is already the limiting factor that determines the southern boundary of forests in western Canada (Hogg and Bernier 2005). Anticipated increases in the frequency and intensity of drought in midcontinental areas will exacerbate the vulnerability of forests at the southern boundary of the forested area of western Canada (Hogg 1994; Hogg and Hurdle 1995; Hogg et al. 2005; Hogg and Bernier 2005).

KEY MESSAGES

EXTREME WEATHER EVENTS

- **The frequency and intensity of extreme weather and climatic events, such as thunderstorms and windstorms, hailstorms, intense precipitation events, drought, heat waves, and abnormally warm winters is likely to increase.**
- **Relatively large increases in the risks associated with extreme weather are possible as early as 2030.**
- **Increased drought frequency and intensity will be a concern in areas that are already dry.**

Windstorms are also a significant disturbance in forests (Dale et al. 2001). In fact, severe wind events are the primary disturbance in eastern deciduous forests in the United States (Peterson 2000). The frequency and intensity of severe storms with high winds (thunderstorms, tornadoes, hurricanes, and tropical storms) will likely increase under climate change. Shallow-rooted species, low-density stands, and some types of stand structure and orientation are particularly vulnerable to wind.

Forest fire

The main factors affecting fire activity are weather and climate, fuel characteristics, ignition agents, and human activities (including fire management). Weather and climate are the primary factor in Canada (Flannigan et al. 2005a, b). It is anticipated that continued warming will result in increased levels of fire activity in many Canadian ecosystems (Stocks et al. 1998; Flannigan et al. 2000; Amiro et al. 2001, 2004; Flannigan et al. 2005a, b), particularly in central and western Canada. Flannigan et al. (2008) suggest that fire management in the circumboreal forest may reach a tipping point within the next twenty years where severe fire years overwhelm fire management resources with increasing frequency. The net result may be a relative increase in area burned greater than the corresponding increase in fire weather severity.

...fire management in the circumboreal forest may reach a tipping point within the next twenty years...

Flannigan et al. (2005b) reported the effects of climate change on future average area burned in modified ecozones across Canada. Their analysis projected a 74% to 118% increase in area burned in Canada in a scenario with 3 times the current atmospheric CO_2 concentration (i.e., by approximately 2080–2100). There is, however, wide variation in the projected effects of fire among the modified ecozones, and in some cases there are significant differences between the results using different general circulation model (GCM) climatic projections. The Flannigan et al. (2005b) study used the Canadian Coupled Global Climate Model (CGCM1) and the United Kingdom's Hadley model to project future climate in the modified ecozones. For example, the average annual area burned in the boreal cordillera ecozone is projected to increase by between 233% (under the CGCM1 model) and 240% (under the Hadley model). The average annual area burned in the western part of the boreal shield ecozone is projected to increase by between 67% and 92%. Projected increases in area burned in the moister eastern half of the boreal shield are between 64% and 74%. The greatest disagreement in the projections using different climatic models occurs in the boreal plains ecozone, where projected increases in area burned range from 9% (using the CGCM1 model) to 245% (using the Hadley model).

Flannigan et al. (2005b) did not consider factors such as expected increases in lightning frequency or increases in fire-season length as potential factors that may affect future area burned. For this reason, projected changes in area burned as a result of climate change may be conservative. Nevertheless, the projected impacts of climate change on area burned are significant. Fire disturbance could be the dominant agent of climate change on forest ecosystems, potentially overshadowing the direct effects on ecosystems (Flannigan et al. 2000). Flannigan et al. (2005a) noted that "fire management agencies operate with a narrow margin between success and failure, a disproportionate number of fires may escape initial attack under a warmer climate, resulting in an increase in area

KEY MESSAGES

FOREST FIRES

- **Climate change will increase the annual area of forest burned.**
- **There will be regional variation in the degree to which climate change affects fires, with higher increases expected in the western and northern portions of Canada than in the eastern portions.**
- **Increases in the frequency and intensity of forest fires will be a dominant agent of change in Canada's forest ecosystems.**
- **The length of the fire season will increase.**

burned much greater than the corresponding increase in fire weather severity…this interplay between climate change and fire is also important in that it could overshadow the direct effects of global warming on plant species distribution and migration."

Although projections of changes in area burned in the study by Flannigan et al. (2005b) are for approximately the period 2080–2100 it is important to note that changes in fire activity are projected to occur in the early and middle years of this century as well. In fact, as noted earlier, recent changes in the climate have already increased forest fire activity. Thus, the effects of climate change on fire activity and the consequent implications for forest management, the forest industry, and forest-based communities are not only of current concern but will become increasingly important over time. Some of the ways that increases in fire activity in the near future may affect human populations include the following:

- increased risk of property loss in communities and increased risk of the need for evacuation
- negative health impacts from increased smoke and airborne particulate matter
- increased fire management costs
- timber supply impacts
- disruptions or delays in harvest operations.

Insect and disease disturbance

Insects and diseases are important agents of change and renewal in forests (Fleming 2000; Volney and Hirsch 2005). Up to the middle part of the last century, Canadian forests co-evolved with native insects and diseases within a relatively stable set of climatic parameters. For example, insect populations fluctuate over periods of years in relatively predictable cycles. When the population of a particular insect peaks within these cycles, an infestation or outbreak occurs. Climate is a key factor affecting the frequency, intensity, and duration of outbreaks (Fleming and Volney 1995; Fleming 1996; Fleming and Candau 1998; Volney and Fleming 2000; Harrington et al. 2001; Boland et al. 2003; Logan et al. 2003; Boland et al. 2004; Candau and Fleming 2005; Fleming 2006; Volney and Fleming 2007; Gray 2008). Climate is also a key factor affecting the geographic range of insect and disease species (Harrington et al. 2001; Juday et al. 2005; Gray 2004; Carroll et al. 2004). Therefore, climate change can influence both the distribution and abundance of insects and diseases (Logan et al. 2003; Carroll et al. 2004; Volney and Hirsch 2005). Warming may have a positive impact on particular insect species if the range of the species is in part determined by temperature, host availability is not restrictive, and climatic conditions influence the frequency, intensity, and duration of outbreaks. This impact may involve more frequent, more intense, more widespread, and longer lasting outbreaks (Fleming and Volney 1995; Fleming 1996, Fleming 2006; Gray 2008). These responses, in turn, have the potential for significant negative impacts on host tree species that are maladapted to combinations of new climate and more vigorous attacks by insects. Forests are particularly vulnerable because short-lived and mobile insect species are generally better able to adapt to rapid climate change than long-lived and relatively stationary host trees (Parker et al. 2000).

The previous paragraph describes a relatively simple picture of insect population dynamics and their response to climate change, but in reality insect population dynamics are complex and very difficult to predict (possibly much more so than wildfire). Dynamic and nonlinear changes in climate will increase the complexity and unpredictability of the effects on insect population dynamics. Higher temperatures may directly enhance the development, reproduction, distribution, and migration of many insect species in Canada (Parker et al. 2000). However, there can be huge variations in responses between species, and there is still much to learn about species-level (insect) response to higher temperatures (Volney and Fleming 2000). Climate change will also have an indirect impact on the distribution and abundance of insects. Insect population dynamics are influenced by complex and dynamic interrelations between abiotic factors (fire, drought, moisture, hydrology, seasonal maximum and minimum temperatures, etc.), biotic factors (parasites, predators, diseases of insects, competitors, availability of hosts, host susceptibility such as tree age, recent history, etc.), forest structure, forest management, and insect and disease control programs. These factors are interrelated and are, in most cases, themselves influenced by climate. In addition, climate and weather affect insect–host tree phenology synchrony (Parker et al. 2000). For example, the emergence of spruce budworm is timed to occur at approximately the same time as buds flush on trees (Volney and Fleming 2007). Freeze events in late spring can kill the new buds and deprive the emerging insects of food.

Dynamic and nonlinear changes in climate will increase the complexity and unpredictability of the effects on insect population dynamics.

Given that climate change is ongoing, its influence on the relations and interrelations between insects, diseases, hosts, and related factors will be continually changing. The complexity of the interactions and feedback between climates, pathogens, and forest ecosystems, however, make it impossible to predict the response of specific pathogens to future climates at specific locations and times (Volney 1996; Parker et al. 2000; Volney and Hirsch 2005). The potential for unanticipated outcomes is high. The potential for unanticipated and unprecedented disturbance events may be one of the most important impacts of climate change on Canada's forests. That is, climate change significantly increases risk of loss and uncertainty relative to our ability to manage forests sustainably and relative to our ability to sustain a stable supply of timber from forests. Additional sources of uncertainty are discussed later.

The spruce budworm is an economically important insect in Canada, particularly in spruce and fir forests in eastern Canada. Gray (2008) found that climate change will result in spruce budworm outbreaks that last longer and produce more defoliation. Other insect species that respond to changes in the climate with potential to cause increased economic impacts on Canada's forests under climate change include the mountain pine beetle (pine), the larch sawfly (larch and tamarack), the spruce bark beetle (white spruce, Engelmann spruce, hybrids), the jack pine budworm (jack pine), the spruce budworm (balsam fir and white spruce), the gypsy moth (hardwoods), the forest tent caterpillar (poplar), and the large aspen tortrix (poplar) (Carroll et al. 2004; Gray 2004; Volney and Hirsch 2005; Juday et al. 2005; Régnière et al. 2005; Fleming 2006; Gray 2008). Insect damage not only has direct impacts on trees but also has indirect impacts on forests. Fleming et al. (2002) noted that there is a positive association between spruce budworm outbreaks and subsequent fire occurrence, suggesting that budworm outbreaks may increase the risk of subsequent fire.

KEY MESSAGES

INSECTS AND DISEASE

- **There is a potential for an increase in the area, duration, and intensity of infestations of spruce budworm, spruce bark beetle, forest tent caterpillar, and the large aspen tortrix.**
- **It is likely that the status of some insects will change from relatively innocuous to severely disruptive.**
- **There will be increased uncertainty about the timing and magnitude of major insect outbreaks.**
- **It is possible that the mountain pine beetle will become endemic to boreal forest regions, with the possibility of periodic outbreaks in jack pine forests.**

An issue of significant concern for forest managers operating in boreal forest areas east of the Rockies is the possibility that a continued warming trend will allow the mountain pine beetle to move into economically important jack pine forests (Carroll et al. 2004). Historically, the principal host species for the mountain pine beetle has been lodgepole pine. However, this insect will attack jack pine as well (Cerezke 1995). The distribution of jack pine is nearly continuous from Alberta to New Brunswick, and many provinces could be affected as global warming continues (Parker et al. 2000; Régnière et al. 2005). With continued global warming, the beetle could expand into boreal forest ecosystems. There are, however, numerous other factors that may limit the insect's expansion, including the fact that jack pine stands in the boreal forest are more sporadic than lodgepole pine in northern British Columbia. Further discussion is available in Logan et al. (2003), Carroll et al. (2004), Régnière et al. (2005), and Taylor et al. (2006).

Effects on physiological processes

At any given forest site, changes in climate will produce changes in average microclimate, with consequent impacts on the physiological processes of photosynthesis and plant respiration and effects on regeneration success, species survival, and primary production (Colombo and Buse 1998; Kirschbaum 2000). Temperature, moisture, nutrient availability, and atmospheric CO_2 concentrations affect the net primary productivity of trees (Aber et al. 2001) and all are expected to change with changing climatic regimes. In some regions, notably at ecotones (which are transition zones between two distinct ecological units) and other vegetation boundaries, even small changes in temperature and precipitation could greatly affect future reproductive success, tree growth, the competitive success of one species over another, and survival (Rehfeldt et al. 1999; Lemmen and Warren 2004). Some species (and genotypes within species) are adapted to relatively narrow environmental ranges and are therefore likely to be more sensitive to small changes in climate and other environmental factors. Genetic adaptation to changes in climate may require several generations (i.e., many decades at least) before species are able to benefit fully from warmer conditions (Beaulieu and Rainville 2005). In the interim, there are risks of increased stress that would reduce productivity and may lead to moderate dieback or even extensive mortality (i.e., local environmental conditions may change faster than the rate at which most tree species are able to regenerate and produce seeds of new, better adapted genotypes). The remainder of this chapter discusses how trees may be affected by changes in temperature, moisture, nutrients, and atmospheric CO_2 concentrations.

A key measure of plant growth is net primary productivity. Net primary productivity is the net amount of the products of photosynthesis after the resources consumed by plant respiration are accounted for (Roy and Saugier 2001). It is calculated as units of biomass produced per unit area per unit of time (e.g., grams per square metre per year). Plant response to temperature is hyperbolic (Aber et al. 2001). Changes in the net primary productivity of plants in response to increases in temperature can be positive (if current temperature is limiting or below the plants' temperature optimum, [i.e., following the temperature increase the products of photosynthesis continue to exceed losses through respiration]) or negative (if the future temperature increase results in tissue death or a situation in which the products consumed through plant respiration exceed those created through photosynthesis) (Aber et al. 2001; Baldocchi and Amthor 2001; Amthor and Baldocchi 2001). Higher temperatures may also result in a longer growing season. However, even a longer growing season can have positive or negative effects on net primary productivity over a year. For example, if water and nutrients are not limiting and temperature is below the optimal temperature threshold, a longer growing season will have positive effects on net primary productivity over a given year. However, if temperature increases result in a situation in which the rate of respiration is higher than the rate of photosynthesis then a longer growing season could magnify declines in net primary productivity (Aber et al. 2001).

Most projections of future climate suggest that precipitation patterns will change to some extent, varying regionally and seasonally and either increasing or decreasing depending on the climatic model or greenhouse gas emissions scenario used. When combined with projections of increasing temperature (which will increase average evaporative demand), the expectation is that some regions will become drier on average, with reduced water supplies to vegetation and reduced water yields from river catchments. Changes in forest productivity will result from changes in water availability during the growing season.

The available water-holding capacity of soils is a critical factor in determining how much water is available for uptake by plants. Work in Saskatchewan has suggested that differences in available water-holding capacity of soils can strongly affect the sensitivity of forest biomass production to a warmer and drier climate (Price et al. 1999). Johnston (2001) found that productivity on sites with low available water-holding capacity (less than 100-mm storage) would likely decline under all future climatic scenarios projected by CGCM1. On sites with moderate available water-holding capacity (100- to 200-mm storage), productivity was projected to increase initially in response to higher temperatures but decrease in later decades. However, sites with high available water-holding capacity (greater than

…differences in available water-holding capacity of soils can strongly affect the sensitivity of forest biomass production to a warmer and drier climate…

200-mm storage) allowed forest productivity to continue to increase during the 21st century because soil water storage would be sufficient to support the increased growth (Johnston 2001). Price et al. (1999) obtained similar results with a modified version of the FORSKA gap model of Prentice et al. (1993), using prescribed changes to present-day temperatures and precipitation at multiple sites along a transect extending from southern Alberta to northern Manitoba. Similarly, Johnston and Williamson (2005) found that productivity of white spruce in Saskatchewan decreased by about 20% on sites with low available water-holding capacity under drought conditions.

With some qualification it can be said that an increase in the atmospheric CO_2 concentration will be beneficial for tree growth (Norby et al. 2005). Reich et al. (2006) found that vegetation responds positively to an increase in CO_2 concentration if nitrogen is available. An enriched atmospheric CO_2 concentration stimulates photosynthesis and increases the efficiency with which trees use their water resources (Baldocchi and Amthor 2001). Under an increased CO_2 concentration, the plant can maintain similar or higher rates of photosynthesis with lower stomatal conductance (Baldocchi and Amthor 2001). Much research, beginning with the groundbreaking work of Farquhar and coworkers in the early 1980s, has established that photosynthesis rates are the primary controller of stomatal functioning (e.g., Wong 1979; Farquhar et al. 1980). Hence, the ratio of water transpired to CO_2 uptake (known as water-use efficiency) will increase as a first-order response to a higher ambient CO_2 concentration (Long et al. 2004). This increase in water-use efficiency could be particularly important at water-limited sites, allowing tree growth to continue where it would otherwise be severely constrained under current CO_2 levels (Aber et al. 2001). Gitay et al. (2001) reported that an elevated CO_2 concentration generally increased water-use efficiency but the magnitude of the response varied with tree age. Many researchers have found that the initial positive response decreases over time as plants acclimate to elevated CO_2 concentrations (Gitay et al. 2001).

Several Free Air CO_2 Enrichment (FACE) experiments are in progress in which young forest stands are exposed to elevated levels of CO_2 (typically double pre-industrial levels) (Norby et al. 2005). No FACE experiments have been conducted in Canada, but there are two sites in the United States that have some relevance to Canada: an aspen forest near Rhinelander in northern Wisconsin, and a loblolly pine plantation at Duke Forest in North Carolina. Results at the pine site have shown that the initial increase in net primary productivity is relatively short-lived (3–4 years) and only occurs when levels of soil nutrients and water levels are relatively high (DeLucia et al. 1999; Oren et al. 2001). In the aspen FACE study, trees were exposed to CO_2, CO_2 combined with ozone (O_3), and O_3 alone. Net primary productivity increased under the CO_2-only treatment but when trees were exposed to CO_2 combined with O_3 their net primary productivity did not differ appreciably from that of untreated trees. Long et al. (2004) carried out a meta-analysis of plant growth at a variety of FACE sites around the world. They found that trees responded more to increased CO_2 concentrations than did other vegetation, with net primary productivity increasing an average of approximately 20%. Norby et al. (2005) found that net primary productivity across a range of FACE sites in Europe and the United States showed a fairly consistent average increase of 23% ± 2% for a doubling of pre-industrial CO_2 concentration. Other work by Körner et al. (2005) showed that there is little increase in the net primary productivity of mature forest trees as a result of elevated atmospheric CO_2

> *Increased CO_2 concentration may result in a short term increase in the water use efficiency of vegetation.*

concentrations. This suggests that the maximum volume a stand can achieve at a given site will not be affected but the period of time a stand takes to reach its maximum volume may be reduced.

Another way that climate change will affect trees in Canada's forests is by changing the relative availability of essential plant nutrients. Nitrogen plays a key role in tree and plant growth in northern forests. However, plant growth in the northern boreal forest is limited by a lack of available nitrogen (Näsholm et al. 1998). Ste-Marie and Houle (2006) found that soil microorganisms in black spruce stands are nitrogen limited mainly because of a short residence time for inorganic nitrogen and low rates of nitrogen mineralization. Studies show that the response of plants to climatic changes will be strongly influenced by how climate change affects the availability of inorganic nitrogen (Reich et al. 2006). This is, however, often not considered in predictions of the future effects of climate change on forest growth.

There are two possible ways that climate change will affect the future availability of inorganic nitrogen to trees. First, because the canopy of conifers can take up to 60% of the inorganic nitrogen brought by rainfall (Houle et al. 1999), there may be changes in the amount of nitrogen available to trees as a result of changes in rainfall patterns. Second, increased soil temperature may increase the decomposition of organic matter, making more nitrogen available to plants (Van Cleve et al. 1990; Kirschbaum 1995; MacDonald et al. 1995; Rustad et al. 2000, 2001; Verburg 2005).

Productivity

It is difficult to determine the net effects of climate change on tree growth because, as noted above, there are many interacting factors (Colombo and Buse 1998; Girardin et al. 2008; O'Neill et al. 2008). Overall, the most important determinant of growth is likely to be the availability of soil moisture. Generally there is potential for forest productivity to decrease in areas that are currently dry but to increase in areas receiving adequate precipitation during the growing season. Regions at risk of a reduction in precipitation during the growing season and an increase in evaporative demand include the southern portions of northwestern and northeastern Ontario, the southern boreal region in western Canada, and hot, dry regions in the southern interior of British Columbia. Further north, where currently there are adequate water supplies during the growing season,[1] there is potential for increased growth as these cold-limited forests experience warmer conditions coupled with higher atmospheric CO_2 concentrations. It should be noted that potential productivity gains resulting from improved physiological conditions for growth may be dampened by maladaptation of local genotypes to the new climate; this will be discussed in later paragraphs.

Juday and colleagues (2005) summarized a number of studies that have looked at the influence of temperature and precipitation on tree growth. One of these studies used a 1000-km north–south transect in central Siberia extending from the northern tree line to the southern forest–steppe ecotone, hence representing a wide range of temperature and moisture conditions, crossing several ecozones. This is similar in concept to the Canadian Forest Service's Boreal Forest Transect Case Study (BFTCS) (Price and Apps 1995), which

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[1] These are likely to remain so according to most general circulation model scenarios.

has included modeling and experimental research over the last decade as well as strong linkages to the Boreal Ecosystem–Atmosphere Study (BOREAS) in 1994–1999 and the Boreal Ecosystem Research and Monitoring Sites (BERMS) experiments conducted as part of Fluxnet-Canada since 1998. Both projects are contributions to an IGBP (International Geosphere–Biosphere Program) Global Change and Terrestrial Ecosystems (GCTE) core project. These studies confirm that warmer summers promote growth in the colder northerly regions. The effects of warmer conditions are less significant in the central regions as long as moisture is not limiting and they are indirectly negative in the south. The effects of increased precipitation, on the other hand, are beneficial in the south (particularly in spring) but have little benefit further north. The climate that is most favorable to growth in the southerly forest–steppe ecotone in Central Siberia appears to be a cool, wet spring and early summer following a cool autumn the previous year.

> *Warm summers promote growth in cold northern regions but have less of an impact in central regions.*

Generally, genotypes of particular species are finely adapted to the climate within which they reside. This is the reason for the current practice of ensuring that regeneration materials (seeds and seedlings) are used in the same general area in which they originated. However, the "local is the best" rule may not be valid in the context of climate change (Wang et al. 2006). Various authors have studied the potential impacts of climate change on local genotypes by studying growth effects when seeds or seedlings of a single species that originated in different climates (i.e., that have a different provenance) are planted at a particular location (or conversely when seeds or seedlings with the same provenance are planted in areas with different climates).

The consequence of planting a particular genotype in a climate that differs from the climate in which it originated can be significant (O'Neill et al. 2008). Carter (1996), for example, compared the growth of balsam fir, larch, white spruce, and jack pine with the same provenances grown at a site in eastern North America where the mean annual temperature was approximately 4°C higher than the area from which they came. The productivity of the jack pine was moderately lower and the productivity of the other tree species was significantly lower at the site with the higher temperature. Andalo et al. (2005) and Beaulieu and Rainville (2005) performed a similar experiment on white spruce genotypes in Quebec. They found that when seedlings were planted in areas with an average temperature approximately 4°C higher than the average temperature at the site of origin, and with precipitation approximately 10% higher than at the site of origin, productivity was significantly lower. Savva et al. (2007) conducted a similar provenance experiment with jack pine and found that when trees with a more northern provenance were planted at a site in Petawawa, Ontario (which is a way of simulating the effects of general warming on genotypes), their radial growth was reduced.

> *The consequence of planting a particular genotype in a climate that differs from the climate in which it originated can be significant.*

Rehfeldt et al. (2004) postulated that given that species will be unable to keep pace with climate change through migration, selection, and gene flows, future climate change will require human intervention in the form of redistributing genotypes to ensure that there is a match between "genotypes" and the "climate for which they are best suited." These findings have important implications for reforestation planning, seed transfers, and forest management. Potential productivity may decrease in some areas and increase in others. However, given the long adaptation lag times for long-lived trees, human intervention in the form of seed transfers may be required to avoid productivity declines and exploit potential productivity gains. Seed transfers across current climatic zones will ensure that trees are better adapted to the environmental conditions that they are expected to face under a future climate (O'Neill and Simpson 2004; Beaulieu and Rainville 2005; Alberta Forest Genetics Resources Council 2007; Savva et al. 2007; O'Neill et al. 2008).

An important implication of this discussion is that changes in climate at the regional or local scale will result in multiple, dynamic, and in some cases competing effects relative to changes in potential site productivity. The net effects may be positive or negative depending on location and the year of prediction. Traditional techniques to estimate growth and yield are based on the estimation of empirical growth using sample-plot remeasurement data. The underlying assumption is that local climate does not change over a stand's rotation length and that historical growth at a site will be representative of future growth. However, this assumption may no longer be valid (O'Neill et al. 2008). There may be, therefore, a need for new approaches to the assessment of forest growth and yield. The approaches most likely to be suitable will make increased use of process-based or empirical models of stand growth that may permit the addition of climate-sensitive adjustments to growth estimates obtained from traditional yield models calibrated against data at the local stand level. Consideration of population differences when modeling growth responses to climate change will also be needed, particularly where climate change results in a maladapted population (O'Neill et al.

KEY MESSAGES

PRODUCTIVITY

- **There is the potential for productivity to increase in more northerly areas with a relatively cold and moist climate and for productivity to decrease in southern areas that are relatively hot and dry.**
- **Local genotypes are finely adapted to an area's current local climate and therefore future climate change will place these genotypes under some stress because they may be unable to acclimatize, adapt, or migrate at the same rate that climatic niches will shift.**
- **Human intervention in the form of redistributing genotypes (e.g., through seed transfers) to try to match them to the future climates for which they are best suited may reduce the negative productivity impacts and enhance potential productivity gains.**
- **Climate change means that traditional empirical approaches to growth and yield estimation that are based on sample-plot remeasurement data may no longer be valid in supporting long-term timber-supply analysis because historical conditions will not match future conditions.**
- **Estimations of future growth and yield may be better informed by developing projections using process-based models and combining these with empirical estimates. However, even with improved projection methods, there will likely be increased uncertainty and variability in timber projections.**

2008). However, given the increasing variability and uncertainty in future growth projections, it may also be necessary to more formally incorporate and link statistical analysis with timber-supply analysis.

A recent analysis by Girardin et al. (2008) showed that different projection-model approaches can provide divergent results in terms of the projected impacts of climate change at a particular site. Their study considered the impact of a climate with 2 times the current CO_2 concentration, using the Canadian second generation coupled global climatic model on jack pine, aspen, and black spruce in Duck Mountain Provincial Park near Swan River, Manitoba. With empirical methods their results indicated a decrease in radial growth whereas their results with process-based methods indicated an increase in net primary productivity. Thus, modeling results can be contradictory.

KEY MESSAGES

FOREST COMPOSITION AND SPECIES DISTRIBUTION

- **Climatically suitable habitats for most species will move northward and will increase in elevation.**
- **The rate of movement in climatically suitable habitats will considerably exceed the ability of individual species to migrate.**
- **New species may be favored at a particular site, but current species have the advantage of site occupation so there may be lags between a change in local climate and a change in species composition.**
- **Forest areas will convert to grassland near current forest-grassland transition zones.**
- **The range of species that are adapted to hot and dry climates will expand into areas that are currently occupied by species that are more suited to cooler and moister climates.**
- **Increases in disturbance will mean that early succession species may be favored, that old-growth stands will become less common, that the average age of forests will decrease, and that average merchantable volumes will decrease.**

An important implication is that a range of models and modeling approaches should be used when assessing the potential impacts of climate change on productivity in a particular area. Projection results are likely to be ambiguous and sometimes contradictory. Given the importance of long-term planning in forest management, uncertainty in projections of future growth and yield under changing climates is one of the fundamental challenges that forest managers will have to face in developing adaptation plans and strategies.

Composition, distribution, and structure of Canada's forested ecosystems

Over time, climate change will lead to changes in species composition and distribution, age-class distribution, and ecosystem structure (Hebda 1998; Li et al. 2000; Kirschbaum 2000; Chuine et al. 2004; Hamman and Wang 2006; McKenney et al. 2007; Aitken et al. 2008). Changes in ecosystems resulting from climate change will be driven by several factors, including effects on physiological processes (as discussed above) (Kirschbaum 2000); the development of new local conditions affecting flowering, pollination, seed formation, and competitive success (Singh and Wheaton 1991); invasion by new species (Dale et al. 2001); differences in the abilities of individual species to acclimatize, adapt, or migrate (Aitken et al. 2008); and changes in spatial and temporal patterns of disturbance agents (fire, insect populations, disease, drought, and extreme weather) (Weber and Flannigan 1997; Volney and Fleming 2000; Volney and Hirsch 2005). The species that will be most successful at adapting to or competing within a changed climate are those that have broad physiological tolerances to climatic conditions, are able to complete their life cycles in short periods of time, and have effective dispersal mechanisms, allowing them to discover new niches and migrate relatively rapidly (Kirschbaum 2000; Gray 2005; Varrin et al. 2007).

As climate continues to change, some species will acclimatize or adapt to new conditions whereas others will not (Gray 2005; Aitken et al. 2008).[2] A rapid change in the climate (i.e., a rate of change that exceeds the ability of species to tolerate, acclimate, or adapt means that current species or genotypes will no longer be suited to an area's local climatic conditions (Gray 2005) whereas new species or different genotypes are favored. As described in the previous paragraphs there may initially be some reductions in productivity. In the longer term there may be a change in the species that grow in the area of interest.

As discussed earlier, disturbances are likely to increase in frequency and intensity under climate change (Dale et al. 2001). Higher rates of disturbance will reduce the average age of forests and hence average stand volumes (Rothman and Hebert 1997). Increased disturbance may also trigger changes in species composition and forest structure (Li et al. 2000). For example, increased disturbance will tend to favor early succession species, such as trembling aspen and jack pine (Thompson et al. 1998). A changing climate would also cause average patch size to change, reductions in the areas of old-growth forest, increases in rates of extinction of local species, and increased areas of forest landscape where ecosystems are actively adapting to new conditions (Thompson et al. 1998; Li et al. 2000; Hansen and Dale 2001).

The work of Brooks et al. (1998), Malcolm et al. (2002), and Juday et al. (2005) suggests that tree species are most likely to respond individually to climate change, with the consequence that biomes and ecosystems will not change as cohesive units (Hebda 2006). The optimal climatic ranges for different species are likely to shift, both in latitude and elevation. Given the rates of warming projected by many general circulation models, shifts in climatically suitable habitats will occur much faster than the capacity of most tree species to migrate (Weber and Flannigan 1997; Parker et al. 2000; Price et al. 2001; Malcolm et al. 2002; Neilson et al. 2005; Aitken et al. 2008). McKenney et al. (2007), for example, estimated that on average the climatic envelopes for major North American tree species will shift northward anywhere from 330 km (assuming nondispersal) to 700 km (assuming full dispersal) by 2070–2100. However, the expected average natural migration rate of plants is about 50 km per century (McKenney et al. 2007).

…shifts in climatically suitable habitats will occur much faster than the capacity of most tree species to migrate.

Soil conditions (i.e., water-holding capacity and nutrient availability) may pose a barrier to the northerly migration of some tree species. The soil-fertility requirements of tree species vary. For example, the forests of southeastern Canada (e.g., sugar maple) have a greater demand for nutrients than northern forests (e.g., sugar maple > balsam fir > black spruce). Although soil-nutrient limitations may limit the northerly migration of some tree species,

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[2] Silverton (1998) defines the ability of individual organisms, including plants, to respond to environmental stimuli within their lifetime as phenotypic plasticity.

higher temperatures do have the potential to improve nutrient availability and increase rates of soil organic pool turnover (Reich et al. 2006), which may offset nutrient limitations in northern soils.

Additional information about expected changes in species composition in specific regions is provided in the next chapter.

Climate-sensitive zones

The impacts of climate change on the composition, structure, and productivity of Canada's forests should be noticeable first (and will be most pronounced) at ecotones (i.e., at transitions between ecological units) and also in island forests (see the paragraphs on the Prairie provinces in the next chapter) because species' sensitivities to changes in limiting factors tend to be highest at these locations (Parker et al. 2000). These areas include the drought-prone southern boreal forests of western Canada (Hogg and Bernier 2005), alpine forest ecosystems (Luckman and Kavanagh 2000; Beniston 2003; Danby and Hik 2007), the northern tree line (MacDonald et al. 1998; Juday et al. 2005), the boreal-temperate forest boundary in southern Ontario and Quebec (Thompson et al. 1998; Parker et al. 2000; Gray 2005); grassland-forest boundary areas in dry zones in southern British Columbia (Hebda 2007), and island forests within the Prairies ecozone (Henderson et al. 2002). Climate-change issues related to these climate-sensitive forest zones are discussed in more detail later in this report.

The boreal forest

The proportion of the circumpolar boreal forest present in Canada is second only to that found in Russia (Shvidenko and Apps 2006). The sensitivity of the boreal forest to climate change is potentially high (Singh and Wheaton 1991; Rizzo and Wiken 1992; Monserud et al. 1993; Neilson 1993; Price and Apps 1995; Weber and Flannigan 1997; Stewart et al. 1998; Price et al. 1999; Shvidenko and Apps 2006; Soja et al. 2007). The IPCC *Second Assessment Report* concluded that the boreal forest is probably more vulnerable to climate change than temperate and tropical forests (Houghton et al. 1996). Kirilenko et al. (2000) suggested that climate change will result in a significant decrease in the aereal extent of the circumpolar boreal forest by 2100.

Important tree species within the North American boreal forest are white spruce, black spruce, tamarack, balsam fir, jack pine, white birch, trembling aspen, and balsam poplar (Volney and Hirsch 2005). These species occur in both pure stands and mixed stands but the form and structure of individual trees, stands, and forest landscapes vary widely owing to variations in climate, terrain, soil characteristics, and other local site conditions. Disturbance has an important influence on species composition and forest structure. For example, in the central boreal plains, stand-replacing fires open areas up for establishment by pioneer species such as aspen (on moister sites) and jack pine (on dry, well-drained, sandy sites) (Volney and Hirsch 2005). Shade-tolerant white spruce becomes established in the understory of aspen stands and eventually forms a mixed stand with both a hardwood and a softwood component. Over time, white spruce becomes dominant. On drier sites, black spruce or aspen will often follow jack pine to form mixed communities. These progressions are periodically perturbed by insect outbreaks that create gaps within stands or sometimes cause complete stand mortality. There are important interactions between fire and insects in the boreal forest in that insect attacks often result in elevated fuel loads for a certain period of time (Fleming et al. 2002; Volney and Hirsch 2005).

White spruce and black spruce are important commercial species in much of Canada's boreal forest, but they could also be the species most sensitive to warming of the climate. Some studies suggest that generally warmer conditions will reduce the net areal coverage of both spruces in the Canadian boreal forest. Brooks et al. (1998) found that an increase in temperature reduced the annual radial growth of black spruce at both the northern and southern BOREAS study sites. Lenihan and Neilson (1995) simulated the responses of white spruce and black spruce in Canada (as well as other species) to two climatic scenarios, obtaining a 20% to 30% reduction in forest areas where these were the dominant species. Similarly, Burton and Cumming (1995) modeled the impacts of climate change on tree species in boreal regions of British Columbia, finding that stands of white spruce and black spruce would probably be replaced by pine over time. Hamann and Wang (2006) found a 52% reduction in the frequency (measured as percentage of ground cover) of white spruce (on the basis of potential habitat) in British Columbia and a 14% reduction in the frequency of black spruce by 2055.

black and white spruce could be the species most sensitive to warming of the climate

Juday and colleagues (2005) also reported on investigations of the effects of climate change on white and black spruce in Alaska and Canada. Higher temperatures over the coming century will have negative impacts on the growth of white spruce on upland sites in central Alaska, leading to the complete disappearance of this species on some sites by 2100. Conversely, increased temperature was projected to have a positive effect on radial growth near the tree line in northern Labrador. On the other hand, black spruce is better adapted to cool, wet sites, causing projected growth to respond negatively to higher summer temperatures at three of four sites in Alaska and at two BOREAS sites in western Canada.

Jack pine is also an abundant and commercially important tree species. Studies simulating the effects of climate change on jack pine have had mixed results. Brooks et al. (1998) found that the growth of jack pine increased with higher temperature and increased spring precipitation. Lenihan and Neilson (1995) indicated that jack pine is intolerant to deep snowpack and will likely be negatively affected in regions where snowpack increases.

Balsam fir has a wide distribution but it is most prominent in forests of the moister eastern boreal region. Similar to spruces, its ecological niches are defined by relatively low soil moisture conditions at the western and southern boundaries of its range and by temperature (i.e., the length and warmth of the growing season) to the north (Ritchie 1987). A combination of drier conditions in the southern portions of its range and warming in the northern portion of its range would therefore likely result in a northward shift of the climatically optimal habitat for balsam fir.

At the landscape scale, a warmer, drier climate will likely drive increases in disturbances, hence tending to favor fire-adapted species (e.g., jack pine and black spruce) and pioneer species (notably aspen and pine species in general) (Thompson et al. 1998). As previously noted, there is considerable concern that progressively milder winters could allow mountain pine beetle populations to spread eastward into boreal stands of jack pine (Carroll et al. 2004), eventually extending across Canada and even into other pine species in eastern Canada and the United States. Given the present-day economic importance of jack pine and its evident potential to replace white and black spruces in a warmer climate, the long-term consequences of a spread of mountain pine beetle populations could be significant.

At the landscape scale, a warmer, drier climate will likely drive increases in disturbances, tending to favor fire-adapted species and pioneer species…

Uncertainty

Although there is certainty that changes in the composition, structure, and age of forests will occur, there is uncertainty about the direction, magnitude, location, and timing of these changes. One source of this uncertainty is uncertainty about the future climate. However, there are a number of other sources of uncertainty. Ecosystems are complex. Many interacting factors will combine to cause a particular response to future climate change and there is uncertainty about what factors will dominate. For example, it is unclear whether the direct effects of climate change on physiological processes will be the most important factor or whether indirect effects through changes in the patterns of disturbance will dominate processes of change. There is uncertainty about the temperature responses of plants to future climate change (Loehle and LeBlanc 1996; Loehle 2000; Norgaard and Baer 2005). Established trees may tolerate changes in climate but they will be unable to compete with new species following disturbance and therefore there may be significant time lags between changes in climate and changes in the composition of forests. There is uncertainty about the long-term effects of CO_2 fertilization and the effects of enriched atmospheric CO_2 concentrations on water-use efficiency (Aber et al. 2001). There is uncertainty in predicting realized species niches (i.e., species niches taking into account interspecies competition) under future climates (Kirschbaum 2000)[3] and about the impacts on ecosystems if tree species are unable to migrate rapidly enough to keep pace with rapid climate change (Dyer 1995; Malcolm et al. 2002).

Uncertainty about how forest ecosystems will respond to future climate change creates many challenges in projecting the impacts of future climate change on forests (Kirilenko et al. 2000; Aber et al. 2001; Neilson et al. 2005). Current models projecting future distributions of ecosystems and plant communities and productivity are limited with respect to how well they consistently account for major changes in disturbances such as fire, physiology (Reynolds et al. 2001), and recruitment (Price et al. 2001). Many models do not distinguish between, or account for, the ability of individual organisms to acclimatize to changes in future climate, the adaptation of genotypes, or human management responses. Finally, many models do not take account of future changes in soil temperature and the

Uncertainties about ecosystem response and the limitiations of existing models have resulted in varying opinions about the effects of climate change.

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[3] Kirschbaum (2000) differentiates between fundamental species niche and realized species niche. The fundamental niche is that area that would be occupied by a species without interspecies competition. The realized niche is that area that is actually occupied by a species (i.e., after interspecies competition has occurred).

potential impacts of climate change on nutrient availability and root development (Houle et al. 1999).

Because of uncertainties about the future and the limitations of both the climatic models and the ecological models, there is a wide range of expert opinion about the possible and probable effects of climate change on the composition and distribution of ecosystems and about rates of migration of northern forests (e.g., Morgan et al. 2001). For example, Lenihan and Neilson (1995) predicted that climate change will result in an overall expansion of Canada's forests, whereas Saporta et al. (1998) suggested that the boreal forest will undergo a significant reduction in size. Similar variations in predictions about the impacts of climate change on forest ecosystems have been noted in the United States (e.g., Aber et al. 2001).

Summary

The relations between climate and forest ecosystems are complex, and predicting the future impacts of climate change on forest ecosystems is equally complex. There are a number of interacting mechanisms and pathways through which climate change will affect forests (Figure 2). Disturbances such as extreme weather, forest fires, insects, and disease will likely increase in frequency, scope, and impact. Changes in disturbance regimes have implications for forest inventory (i.e., it will likely decrease), for the age of forests (i.e., forests will likely become younger), and for species composition (i.e., pioneer species [species that are the first to occupy a site after disturbance] will become more common). Water and nutrient availability will change from location to location. The growing season will likely lengthen and winters will become less harsh. Average temperatures during growing seasons are expected to increase and this could either decrease or increase net primary productivity (depending on whether a particular organism is at the southern or northern part of its range). Average temperatures during winters will also increase, possibly favoring species that are less cold sensitive and harming species that are specialized and adapted to cold climate. Warming winters will result in reduced mortality of many damaging insects. There will be changes in freeze–thaw cycles. Climate change will also affect biological and ecological processes, such as photosynthesis, respiration, regeneration, succession, growth, and mortality.

Climate change will result in new temporary ecological niches that will favor new species over existing species at particular sites. However, current species have the advantage of site occupation so there may be significant lags between when the climate changes and when forests respond. All of this means that climate change has implications in terms of changes in commercial forest stocks (or inventory), changes in the availability of commercially important species, and changes in yields. Impacts will vary over time and they will vary from location to location. Given the complexity of the interactions between climate and forests, the dynamic nature of climate change, and the uncertainty about change in future climate and in forest response, it is not possible to provide a comprehensive and unambiguous story of the impacts of future climate change on forests at a national scale. Nevertheless, a general picture is emerging. The research described in this chapter shows that the impacts of climate change on forests are likely to be significant and will increase in scale and importance over time. Moreover, adaptation has the potential to mitigate or reduce some of these impacts. Adaptation issues and options for Canadian forestry are discussed in more detail in Chapter 6.

There is a significant and growing body of Canadian scientific literature that provides a solid basis for beginning to understand the impacts of climate change on forests. However, more research is needed to reduce uncertainty and support adaptation policy-making and decision-making. But more research by itself is not enough. Because of the crosscutting nature of climate change, scientific research will need to be coordinated and integrated across organizations and across disciplines. Most importantly, because climate change has such important implications for forest policy, there will need to be a strengthening of science–policy linkages.

REGIONAL FOREST VULNERABILITIES

The forests in each region of Canada have distinctive features and are likely to be affected by climate change in unique ways. Previous chapters have considered current and potential future impacts of climate change on Canada's forests and forest sector in a general way. This chapter describes how climate change may affect forests at a regional level.

The North

> *In the North traditional activities, caribou, and transportation systems may all be negatively affected by climate change*

The boreal forest of the Yukon and the Northwest Territories comprises about 13% of Canada's total forest cover (Nunavut is above the tree line and is not considered in this report). Commercial forestry is relatively small in scale compared with that in the southern provinces, but it is nevertheless an important economic activity in a number of northern communities (Rothman and Herbert 1997). Northern forests are also of crucial importance to the cultural, social, and economic well-being of Aboriginal peoples and indigenous communities in the Yukon and Northwest Territories (Cohen 1997) and play a significant role in traditional and spiritual activities. Along with hunting and trapping, the gathering of medicinal plants, berries, and mushrooms is an important subsistence activity in northern forests (Nuttall et al. 2005). The continuation or persistence of some traditional activities may be threatened by the ecosystem changes anticipated as a result of climate change (Cohen 1997). For example, both woodland and barren-ground caribou are culturally and economically important to northern indigenous communities. An increased frequency of forest fires and other factors related to climate change may harm woodland caribou populations (Arctic Council 2005). At the same time, the northward movement of the forest–tundra ecotone may displace barren-ground caribou habitat and modify migration routes (Nuttall et al. 2005). Other concerns for northern communities include disrupted transportation systems owing to loss of ice roads, destabilization of buildings and infrastructure because of permafrost melting, reduced predictability of weather owing to increased weather variability, and increased risk of adverse exposure because of increases in extreme weather (Arctic Council 2005; Furgal and Prowse 2008).

Northern forest ecosystems are adapted to cold climate and are therefore particularly sensitive to climate change (Cohen 1997; Juday et al. 2005; Furgal and Prowse 2008). Recent relatively minor changes in the climate have already had significant effects on northern ecosystems, including abnormal wildfires, unprecedented insect outbreaks (e.g., spruce bark beetle), and forest declines associated with permafrost melting (Parmesan and Yohe 2003; Juday et al. 2005; Jorgenson and Osterkamp 2005; Arctic Council 2005; Scholze et al. 2006; Ogden 2006). The summer of 2004 was the warmest on record in the Yukon. Record temperatures combined with below-normal precipitation, a record number of lightning strikes and a longer lightning season (Green 2004) resulted in a record year for forest fires in the Yukon. This had both positive and negative impacts. On the negative side, it meant some loss in timber values and the need to increase salvage operations. On the positive side, the fire season of 2004 resulted in a large harvest of morel mushrooms, a lucrative species that is abundant in forests following fires (see Government of Yukon <http://www.gov.yk.ca/news/2005/05-196.html>).

Future climate change is projected to be much more significant in the North than in southern latitudes (Houghton et al. 1996; Arctic Council 2005; Furgal and Prowse 2008). Dramatic impacts on northern forest ecosystems are anticipated. Also, the North is relatively sparsely populated and financial resources for adapting to climate change (e.g., in terms of increasing resources for forest protection) are limited. The combination of high exposure, high sensitivity, and constraints on adaptive capacity indicates that the forests and forest values in the Yukon and Northwest Territories have a relatively high level of vulnerability to climate change.

Future climate change is projected to be much more significant in the North than in southern latitudes.

The most significant impacts on forests in the North are expected to include northward movement of the tree line, increases in wildfire disturbance, and melting of large areas of permafrost (with negative consequences on the forests growing on these lands). The northern tree line is generally considered to be limited by cold temperatures (Price and Apps 1995; Price et al. 1999). It is expected that warming will result in movement of the forest–taiga boundary northward but not in a smooth and continuous way (Payette et al. 2001; Juday et al. 2005; Danby and Hik 2007). MacDonald et al. (1998) suggested that future warming may increase tree growth and productivity at the tree line and that recruitment of white and black spruce will increase but that there may be a considerable time lag between the creation of new climatically suited niches and occupation because the rate of dispersal of some tree species is expected to be slower than the rate of future climate change (Arctic Council 2005; Juday et al. 2005). Payette et al. (2001) suggested that the tree line is not a discrete line. Rather, it is a broad zone that runs from the boundary of continuous coniferous forest cover all the way to the boundary of continuous arctic tundra. The forest–tundra ecotone comprises a complex "constellation of subarctic tree lines" with forest occupying lower, moist, and protected areas and tundra occupying higher, exposed, well-drained sites. They noted that the northern forest–tundra ecotone will respond to climate change through tundra-to-forest shifts that will occur as trees fill in sites that are currently considered as tundra sites and through forest-to-tundra shifts caused by fire disturbance. Thus, the response of northern forests to climate change will be complex and nonlinear.

Climate change is expected to increase the frequency, extent, and severity of forest fires in the north. This will result in a reduction in the mean fire-return intervals, a shift in age-class distribution toward younger forests, and a decrease in terrestrial carbon stored in the northern boreal forest (Flannigan et al. 2000; Stocks et al. 2002; Juday et al. 2005; McCoy and Burn 2005). Historically, lightning activity in the southwest Yukon region has been low, resulting in a relatively long fire cycle (Francis 1996; Ogden 2006). However, recent climate warming may be contributing to increased lightning activity in the North (Green 2004). Fosberg et al. (1990) and Price and Rind (1994) suggested that climate change will increase lightning activity. Climate change will result in higher temperatures during the fire season and longer fire seasons in the North. Flannigan and colleagues (2005b) projected an 80% (using the Canadian climatic model) to 90% (using the Hadley climatic model) increase in total area burned in the northern forest zones under a scenario with 3 times the current CO_2 concentration (i.e., by about 2080).

Climate warming in permafrost regions may result in deeper seasonal thawing and the eventual conversion of large areas of permafrost soils to wetland systems. Hence, northern boreal forests presently growing in permafrost regions could become treed wetlands (Gray 2005). Smith and Burgess (1999) estimated that the present-day Canadian permafrost region could be reduced to one-half its present area by 2050. Camill (2005) reported that rapid thawing of permafrost is already occurring as a result of warming since the 1940s. Osterkamp et al. (2000) reported that significant areas of the boreal forest in Alaska were transformed into wetlands during the last 20 years of the 20th century.

The significant vulnerability of northern forests to climate change means that climate change must be taken into consideration in decisions regarding forest management and planning in the North (Ogden and Innes 2007b). Forestry practitioners in the Yukon and Northwest Territories were asked to complete a survey about the probable impacts of climate change on the sustainability of the forest sector and their options for adaptation to climate change (Ogden and Innes 2007a). Changes in the intensity, severity, or magnitude of insect outbreaks, changes in extreme weather events, and changes in the intensity, severity, or magnitude of forest fires were the three impacts most frequently identified as being likely to have an impact on sustainability. However, more than half of the respondents indicated that commodity prices, availability of timber, trade policies, environmental regulations, and the ability to secure needed capital were having more of a negative impact on sustainability at present than climate change.

British Columbia

British Columbia is Canada's largest producer of wood products. Total revenues earned by the forest industry in this province from the sale of wood-based products (such as lumber, oriented strand board, shingles, pulp, and paper) were about $22.3 billion in 2005 (<http://canadaforests.nrcan.gc.ca/statsprofile/bc> accessed 4 Nov. 2007). Most of this revenue was derived from the sale of forest products to consumers in foreign markets. Similar to forests in other provinces, British Columbia's forests also provide many other benefits. Mushrooms, berries, and botanicals are important nontimber products. Forests help to regulate water supply and contribute to water quality. They provide habitat for fish and other wildlife, are important reserves for endangered species, provide areas for recreation in all seasons, contribute to British Columbia's appeal as a tourist destination, and are culturally and spiritually significant to the province's population. Climate change has the potential to affect all of these uses and values.

British Columbia is both a coastal and a mountainous province. The province's climate varies widely and the terrain and landscape are diverse. Its forests are the most productive and ecologically diverse of the forests of any province in Canada. The principal sources of vulnerability to climate change for British Columbia's forests and forest sector are as follows:

- restructured global markets with implications for British Columbia's exports
- increased fire disturbance
- increased losses from insect damage and disease

- increased frequency and intensity of droughts in the southern interior portions of the province that are currently drought prone
- species migration and changes in forest productivity
- loss of habitat in high-elevation forests.

The British Columbia Ministry of Forests and Range (2006) described the potential impacts of climate change on the major tree species in the province.

Lodgepole pine: Lodgepole pine will continue to be susceptible to mountain pine beetle. Mountain pine beetle is attacking and killing trees 60 years younger than was previously thought possible. Dothistroma needle blight and other foliar diseases of lodegepole pine are also of concern. These diseases are on the increase. There is the potential for the productivity of lodgepole pine to increase in the northern interior in the near to mid term with moderate increases in temperature (i.e., 2 °C or less) but this species may be susceptible to higher temperature increases if seed sources are not moved (Wang et al. 2006). Lodgepole pine will be favored over Douglas-fir if future climates are warmer and drier; Douglas-fir will be favored over lodgepole pine if future climates are warmer and moister (Nigh et al. 2004).

Douglas-fir: Douglas-fir may replace or at least supplement lodgepole pine in the sub-boreal spruce biogeoclimatic zones as lodgepole pine suffers increasingly from pests under climate change. However, in drier ecosystems, interior Douglas-fir will be drought stressed. Spruce budworm and other insect defoliators and Armillaria and laminated root diseases will follow any northward movement of interior Douglas-fir. Nigh (2006) used cross-sectional data to model the effect of temperature, nutrient regime, and moisture regime on coastal Douglas-fir site index and found that the temperature and moisture response of coastal Douglas-fir site index is positive (i.e., sites with a higher ambient temperature and with more moisture have a higher site index). Thus, increasing temperature will likely have a positive effect on growth. However, future climate change will likely have a major impact on costal Douglas-fir, with increased water demand. Spittlehouse (2003) calculated summer potential evaporation for a range of climatic scenarios in the Georgia Basin and found that Douglas-fir productivity declined from 10% to 30% over the life of a stand owing to reduced moisture availability.

Western hemlock: The survival of western hemlock and potential expansion of its range under climate change will depend on the balance between changes in evaporative demand and water availability. Any increase in moisture availability (i.e., precipitation minus evaporation) will likely be a benefit. However, the species will likely suffer greater losses to insect defoliators under climate change.

Larch (western and Siberian): Larch may cope well with drought and could supplement lodgepole pine in the sub-boreal zone under climate change. In areas where there is increased summer precipitation, these species will be susceptible to losses to foliar diseases.

Spruce: Spruce is expected to suffer losses owing to leader weevils and to foliar diseases. Productivity may increase with a longer growing season and higher temperatures, particularly if summer precipitation in central and northern British Columbia increases as predicted.

Western redcedar: This species could be well suited to conditions under climate change in the northern interior forest region. It is less susceptible to Armillaria root disease than other species in the region. Western redcedar may prove to be a valuable species for areas that are heavily infested with that pathogen. On the coast, western redcedar will likely disappear from drier sites where it is already marginal.

Subalpine fir: Subalpine fir grows at high elevations in the interior of British Columbia where summers are cool and winters are cold.[1] The range of subalpine fir is likely to be reduced at lower elevations with warmer conditions. There is an increased risk of balsam woolly adelgid spreading into interior forests. Subalpine fir is also susceptible to wood-rotting fungi. Lichens growing on the lower branches of subalpine fir are an important food source for caribou and therefore a reduction in the occurrence of these trees may have negative consequences for caribou populations.

Climate change is projected to have the following regional impacts within British Columbia:

Coastal forests: In the south, warmer and drier weather in late spring and summer could increase fire risk and decrease water availability. Increased water stress will affect species such as western redcedar on marginal sites on the east side of Vancouver Island. The mid and northern coasts, which are presently wet and cool, are expected to see an improvement in growing conditions. An increase in storm frequency and intensity will likely increase windthrow and breakage of trees. An increase in the severity of storms could increase the probability of occurrence of landslides, including debris flow activity.

Southern interior (lower elevations): Drier conditions are expected and there is the possibility of increased frequency and intensity of droughts. This will have negative implications for regeneration, growth, and mortality. Grassland ecosystems may replace forest ecosystems in dry areas in the southern interior over time (Hebda 2006, 2007).

Southern interior (higher elevations): Some benefits can be expected from a shorter snow season and a longer growing season. However, reduced precipitation and temperature increases may result in increased risk of fire and drought stress.

Northern interior: Some increases in tree growth and small changes in summer precipitation can be expected in the near term as a result of climate warming. Shorter winter seasons will result in reduced access to sensitive terrain in some areas.

Hamman and Wang (2006) used an ecosystem-based climatic envelope model to assess how tree species niches and biogeoclimatic zones in British Columbia might change. The study looked at current climatic niches for trees and biogeoclimatic zones and compared these with future species and ecological niches on the basis of climatic projections from the CGCM1 climatic model using the IS92a emission scenario (Leggett et al. 1992). Tree species with their northern range limit in British Columbia will gain suitable habitat at a pace of at least 100 km per decade (although as previously noted the actual speed at which trees can migrate is about 5 km per decade on average). Common hardwoods appear to be less sensitive to climate change whereas some of the most important conifer species in British Columbia could lose a large portion of their climatically suitable habitat. Hamman and Wang (2006) reported that the following biogeoclimatic ecological zones will increase in area by 2085: bunchgrass, coastal Douglas-fir, coastal western hemlock,

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[1] <http:www.for.gov.bc.ca/hfd/library/documents/treebook/subalpinefir.htm> accessed 10 Nov. 2007.

interior cedar hemlock, interior Douglas-fir, and ponderosa pine. The following ecological zones are projected to decrease in area by 2085: alpine tundra, boreal spruce, Engelmann spruce, subalpine fir, mountain hemlock, montane spruce, sub-boreal pine and spruce, sub-boreal spruce, and spruce-willow-birch.

There is little available information about how nontimber goods and services such as botanical forest products, mushrooms, berries, floral greens, medicinal plants, and forest-based outdoor recreation will be affected by a changing climate. The harvest of botanical forest products is a growing industry in British Columbia. The cultural and economic effects of climate change on this industry could be large. Increases in disturbance by fire may favor certain mushroom species and shrubs. In terms of outdoor recreation, warmer winters will shorten the winter recreational season whereas the summer recreational season will lengthen. However, increases in fire risk may limit summer outdoor recreation.

The range of many species will move upward in elevation, making high-altitude alpine forests vulnerable to extinction and reducing niches for subalpine conifers such as Engelmann spruce, mountain hemlock, and several fir species (Hansen and Dale 2001). Laroque and Smith (2003) projected significant declines in radial growth of high-elevation mountain hemlock on Vancouver Island by 2100. Luckman and Kavanagh (2000) in fact found that the tree line has already moved upslope in response to 20th-century climate change in the Canadian Rockies. In a study of alpine tree dynamics, Danby and Hik (2007) noted that the tree line is not moving gradually upward in response to climate change, but rather the changes observed to date suggest a threshold response (i.e., some degree of change in climate with no observed impact followed by a sudden shift).

...the tree line has already moved upslope in response to 20th-century climate change in the Canadian Rockies.

Prairie provinces

The boreal forest is the dominant forest ecosystem in the Prairie province region. Much of the discussion on the boreal forest in the previous chapter also pertains to how climate change will affect forests in the Prairie provinces.

The boundary of the southern edge of the boreal forest in western Canada corresponds closely with moisture availability (Hogg 1994, 1997). Further drying will be a major source of vulnerability in the prairie-forest grassland ecotone of western Canada. In the driest areas of the boreal forest, losses of forest cover are expected over time and some closed-cover forest areas will convert to aspen parkland type conditions. Predicted increases in precipitation in the region are likely to be offset by the increases in evaporation that are expected to result from higher temperatures. Half of the western Canadian boreal forest could become exposed to a drier climate, similar to that in the present aspen parkland zone. Future changes in climate could therefore result in permanent losses of forest cover following disturbance and important reductions in forest productivity in the southern boreal forest (Hogg and Hurdle 1995).

In the Prairie provinces, climate change could result in permanent losses of forest cover in the southern boreal forest.

Climatic scenarios for the Prairie provinces suggest that the future will bring warmer winters with greater precipitation and earlier springs (Flato et al. 2000; McDonald et al.

2004; Barnett et al. 2005). Summers may be somewhat warmer but they will be drier because of increased evaporation (Laprise et al. 2003; Wang 2005), and extreme precipitation and drought events may become more frequent (Sauchyn et al. 2003). Excess spring moisture from earlier and heavier snowmelt, earlier and perhaps longer weight restrictions on roads during the spring, and waterlogged conditions in operating areas can be expected. This could affect both woods operations and the construction and use of forest roads. Harvesting operations and wood transport that depend on frozen ground would also be vulnerable to warmer winters, resulting in a reduced haul season.

Forest fires are expected to be more frequent (Bergeron et al. 2004) and of higher intensity (Parisien et al. 2004, 2005) and to burn over larger areas (Flannigan et al. 2005b) in the Prairie provinces. Insect outbreaks are also expected to be more frequent and severe (Volney and Fleming 2000). The long-term effect of insect outbreaks on forest management is difficult to predict but recent research suggests that tree mortality will increase as a result of the interaction of insects, drought, and fire in the southern margin of the boreal forest in the Prairie provinces (Hogg and Bernier 2005; Volney and Hirsch 2005).

Some coniferous species are more flammable than hardwood species (Parisien et al. 2004) so increased forest fire activity will likely encourage early succession species (such as jack pine, aspen, lodgepole pine) instead of late succession species (such as white spruce and balsam fir). Conifers such as jack pine are well adapted to reproduce following fire, so a long-term increase in fire frequency may lead to an increase in aspen and jack pine at the expense of spruce and other species.

There are a number of small pockets of forest scattered across the open prairie grasslands of western Canada. These pockets of forests are referred to as island forests. Henderson et al. (2002) investigated the potential impacts of climate change on a number of sites including the Cypress Hills (crossing the southern Saskatchewan–Alberta border), Turtle Mountain (just north of the US border in southern Manitoba), Spruce Woods (just north and east of Turtle Mountain), and Moose Mountain (in southern Saskatchewan near the Manitoba border). In Cypress Hills there will be an increased risk of insect infestations and fire with climate change. Regeneration of the dominant tree species (lodgepole pine and white spruce) will become increasing difficult because of the drier conditions. The landscape will transform from one in which there is a continuous forest cover to a patchy landscape where small patches of trees continue to exist, but only in sheltered sites. Turtle Mountain is vulnerable to climate change because of drying and drought. Bur oak may replace some aspen over time.

Aspen within the Spruce Woods forest will decline over time and will possibly be replaced by bur oak on some sites. The Moose Mountain forest is highly vulnerable to climate change because of drying. It is expected to shift from relatively continuous forest cover to an open parkland type forest consisting of patches of trees interspersed with shrub and grassland.

Ontario

Climate change will increase fire activity in Ontario owing to increased temperatures combined with increased frequency and severity of drought years (Flannigan and Van Wagner 1991; Simard 1997; McAlpine 1998; Wotton et al. 2003; Gillett et al. 2004). A hotter, drier climate will increase the number of "fire flaps." A fire flap results from an increase in fire danger caused by several weeks with no or little rain, coupled with an ignition source, especially lightning. In Ontario, fires ignited by lightning comprise 80% of the burned forest area (McAlpine 1998). Fosberg et al. (1990) and Price and Rind (1994) found that climate change may result in an increase in lightning activity.

Climate change is predicted to increase the number of fires in Ontario (Wotton et al. 2003) and area of forest burned in Ontario by between 1.5 and 4 times by the latter part of the century (Flannigan et al. 2005b). This increase in area burned will be highest in northwestern Ontario's boreal forest, where fire suppression is not practised. Ward et al. (2001) estimated that 0.34% of the far northwest forest burns annually (a fire return interval of about 294 years). In comparison, intensive fire suppression in more southerly portions of the boreal forest limits the burned area to about 0.11% of the total forest per year (Ward et al. 2001) (a fire return interval of about 900 years).

Longer droughts and higher temperatures resulting from climate change may create a tipping point whereby fires become unmanageable in some years. In theory this could cause even greater increases in the average area burned than predicted by Flannigan et al. (2005b). Maintaining the current rate of burn in the managed boreal forest will require increased investment in fire management. However, in extreme years, elevated fire-suppression efforts may be unable to prevent large fires.

Large areas of forest in Ontario are affected by outbreaks of spruce budworm and forest tent caterpillar, and these pests will be influenced by climate change. Spruce budworm, currently the most damaging forest insect in Ontario, is predicted to become more damaging in northern parts of the boreal forest and less damaging in southern parts of boreal forest in Ontario (Candau and Fleming 2005). A combination of increased drought and insect defoliation of aspen is predicted to decrease growth and increase the risk of aspen dieback in boreal forests near the Ontario–Manitoba border (Hogg and Bernier 2005).

Warmer winter climates could permit expansion of tree species now near their northern range limit. However, the northern migration of tree species will not match the rate of shift in climate that is expected this century (Roberts 1989; Loehle 2000; McKenney et al. 2007). Even long-distance dispersal events (Clark 1998; Higgins et al. 2003) would not enable species to move in step with climate change. More southerly forest types (e.g., the oak–hickory forests of southwestern Ontario, south-central Minnesota, and Michigan) would require hundreds of years to naturally migrate to the current boreal forest zone (Davis 1989; Roberts 1989). Aside from local expansions of species near their northern range limits, the only significant changes in the composition of tree species attributable to climate change in the near term will be changes in the relative abundances of species that are already common in the area. For example, climate change may favor disturbance-adapted species more than has been the case in Ontario historically.

The increase in forest fires in the boreal forest will remove standing forests at an increased rate in the future (Flannigan et al. 2005a). This will likely contribute to an increase in the number of early-succession ecosystems dominated by fire-adapted species, such as jack pine, black spruce, white birch, and aspen. During periods of drought, drought-prone sites will tend to be reestablished by drought-tolerant species (Grime 1993; Bazzaz 1996). In the boreal forest this process will favor species such as jack pine and aspen at the expense of species such as black spruce and balsam fir. In the Great Lakes – St. Lawrence forest region there may be episodes of drought that lead to early stand dieback and breakup (Overpeck et al. 1990). In these ecosystems, xeric species (i.e., species adapted to dry conditions) such as red maple, white pine, and red oak will be favored over mesic species (i.e., species adapted to moist conditions) such as sugar maple and eastern hemlock.

In addition to having effects on tree species, climate change will result in contractions and expansions of the ranges of Ontario wildlife. Varrin et al. (2007) reviewed published scientific studies investigating the impacts of climate change on vertebrate species that occur in Ontario and found that of the 175 species studied, the ranges of 10 species are expected to contract, the ranges of 62 species could expand, and the responses of 103 species are equivocal.

The Great Lakes – St Lawrence forest region is located along the southern border of the boreal shield ecozone in Ontario and Quebec. Temperate deciduous and coniferous forests dominate, including maple, basswood, oak, and white pine (Colombo et al. 1998). It is expected that warming will result in a shift of the Great Lakes – St. Lawrence forest northward into the boreal shield ecozone (Colombo et al. 1998; Thompson et al. 1998; Parker et al. 2000; Gray 2005). This expectation is supported by paleoecological evidence that suggests that the Great Lakes – St. Lawrence ecosystem existed as far north as Timmins, Ontario, during a warm period from 7000 to 3000 BC (Liu 1990; Gray 2005). Replacement of boreal forest by temperate forest will only occur, however, in areas where fire regimes do not increase (Thompson et al. 1998). Moreover, as noted previously it is unlikely that the overall rate of species migration will keep pace with the rate with which suitable climatic niches are created as a result of climate change (Parker et al. 2000). Therefore, it is unlikely that there will be a wholesale and smooth shift from boreal forest to a Great Lakes – St. Lawrence type of forest (Thompson et al. 1998; Parker et al. 2000).

In Ontario's deciduous-boreal forest, sugar maple has the greatest potential for increased growth.

Goldblum and Rigg (2005) used tree-ring data and pollen analysis to look at the changes in growth and abundance of sugar maple, white spruce, and balsam fir in response to changes in climatic regimes during the Holocene for an area 200 km north of Sault Ste. Marie, Ontario. They employed correlations between climate and growth and used these in combination with GCM projections to project growth of sugar maple, white spruce, and balsam fir at the deciduous–boreal forest ecotone in Ontario. They concluded that sugar maple has the greatest potential for increased growth over the next 80 years. White spruce will benefit less and balsam fir will likely experience a decrease in productivity. In terms of abundance, species currently common in the Great Lakes – St. Lawrence forest region of southern Ontario and Quebec are expected to gradually migrate northward under climate change (although at different rates). Tree species that will be favored by climate change and that are likely to become more common in the area that is currently occupied by the southern portions of the boreal shield will be temperate species such as maple and white pine (assuming the more northerly soils are rich enough [with respect to the higher nutrient requirements of maple and white pine] to support these species).

A recent study by Browne and Hunt (2007) summarized the impacts of climate change on nature-based tourism, outdoor recreation, and the forest sector in Ontario. They reported that climate change is expected to have a net positive effect on nature-based tourism and outdoor recreation in Ontario, and participation in snow- and ice-based activities will likely decrease because of shortened seasons." They also reported that Ontario's producers of traditional forest products are expected to experience negative effects from climate change. Supplies of wood fiber in Ontario are expected to decline, whereas the costs of tending, extracting, and milling are expected to increase. These changes will occur at the same time as global timber supply is expected to increase and global prices for forest products are expected to decrease.

Quebec

Three large forest types comprise Quebec's forested landscape. From south to north, these are maple forests, fir forests, and spruce forest. The significant warming observed over the last century has already altered forest composition. Signs of a longer growing season are already evident. For example, Bernier and Houle (2005) found that sugar maple bud burst now occurs several days earlier than it did 100 years ago.

The projected annual increase in average temperature for central Quebec of 3.2 °C by 2050 would translate to a movement of climatic zones 515 km northward, which translates to a speed of approximately 10 km annually. As noted previously, this speed is much faster than the fastest observed migration speeds of trees (Malcolm et al. 2002). Also, given the different dispersal methods between species and the differences in the physiological responses of species to changes in climate, species will migrate at different rates. This is likely to result in species assemblages that have not previously been experienced. Soil fertility could also limit tree migration because forests' nutrient requirements vary by type of stand (e.g., the nutrient requirements of a maple forest are higher than those of a fir forest, which are higher than those of a spruce forest [Ste-Marie and Houle 2006]). However, as noted in the previous chapter, temperature increases associated with climate change may also improve the availability of soil nutrients, particularly inorganic nitrogen.

There are several possible impacts of climate change on insects outbreaks in Quebec forests. The range of the spruce budworm could increase significantly (moreover, according to Gray 2008, outbreaks may be longer lasting and defoliation will increase), the range of gypsy moth may expand (Gray 2004), the mountain pine beetle may spread from west to east in boreal forests (Carroll et al. 2004), and the Asian long-horned beetle could expand its range into areas currently occupied by maples, elms, and poplars (Cavey et al. 1998).

Although most climatic models predict an increase in the frequency of fires in the northern hemisphere owing to a longer growing season and more frequent lightning strikes (Wotton and Flannigan 1993), the situation is different in Quebec. The frequency of wildfires in Quebec is expected to increase in the western and northern regions, decrease in the eastern region, and remain constant in the central region (Bergeron et al. 2004).

In Quebec, shorter winters have required changes in forestry operations.

Decreases in the length of winters have direct and immediate impacts on forest management planning on and forestry operations; these impacts include reduced periods of winter access, increased potential for adverse soil impacts, and increased seasonality of employment. Forestry practices must therefore change in response to decreases in the length of winters. These kinds of direct impact are currently the primary concern of forestry companies. The thinning and discontinuity of snow cover as well as the early melting of snow cover are sources of concern for forest managers in hardwood-forest regions in southern Quebec, because soil exposed to open air is susceptible to deeper frosts. Freezing at the root layer of trees causes substantial root damage, which can significantly affect soil chemistry and growth for a number of years (Boutin and Robitaille 1995).

Atlantic Canada

There are two major forest types in Atlantic Canada: the Acadian forest (which stretches across the Maritime provinces of Nova Scotia, New Brunswick, and Prince Edward Island) and the boreal forest (located in Newfoundland and Labrador). Forests cover high proportions of the land in all of the Atlantic provinces, from 47% in Prince Edward Island to 86% in New Brunswick. As a result, forestry is fundamental to the economy of Atlantic Canada. The forests of the Maritime provinces (Nova Scotia, New Brunswick, and Prince Edward Island) are predominantly privately owned. The forests of Newfoundland, on the other hand, are publicly owned. The Acadian forests of the Maritime provinces are quite mixed whereas the boreal forests of Newfoundland are largely coniferous.

Forest management practices in the Atlantic provinces have been dominated by planting, fire suppression, and control of insects and browsers (Ayres and Lombardo 2000; Etheridge et al. 2005), which in turn have altered the distribution of forest species. The reversion of agricultural land to forest, in the Maritimes in particular, has increased the proportion of early successional species such as balsam fir and white spruce in forests (Loo and Ives 2003).

The distribution of native species in Atlantic Canada's forests is expected to shift with future climate change. On one hand, some native tree species should, to a degree, be able to maintain their normal distribution despite climatic shifts (Chapin et al. 2004). Some tree species may have difficulty persisting in the Maritimes under a changing climate (e.g., balsam fir), whereas those able to persist will become more prevalent. Because tree-species migration is such a slow process, an influx of tree species common to the Carolinian forest of the northeastern United States is unlikely to occur during the 21st century unless assisted through planting programs. Introduced species that have an inherent ability to outcompete native species with shifting climatic conditions could gain footholds, drastically altering the current distribution of native species (Simberloff 2000).

Balsam fir may have difficulty persisting in the Maritimes under a changing climate.

Insects are a primary cause of disturbance in both the Acadian (Etheridge et al. 2005) and the boreal (Bergeron et al. 2002) forests of Atlantic Canada. Spruce budworm in particular represents a significant source of forest disturbance in the forests of Atlantic Canada. The potential increases in windthrow and drought and the milder winters expected in a changed climate will only increase the vulnerability of Atlantic forests to such insects (Fleming and Candau 1998). Other species that will contribute to the vulnerability of

Atlantic forests in the future include the spruce beetle and the hemlock woolly adelgid. The former is an opportunistic native species that takes advantage of windthrown trees.

The latter species, currently excluded from Atlantic Canada by winter temperatures, may capitalize on moderate winters and could alter the composition of Atlantic Canadian forests by killing the eastern hemlock component of Acadian forests as it has done in the United States.

Pathogens also contribute to the vulnerability of forests. In particular Dutch elm disease, butternut canker, and beech bark disease have had a significant impact on the hardwoods of the Acadian forest region over the past century (Loo and Ives 2003). The effects of existing pathogens may increase because of the stress that climate change will have on established forest species (Ayres and Lombardo 2000). Pathogenic outbreaks not currently known in the region such as those favored by warmer winter conditions (Bertrand and Castonguay 2003) may also increase in incidence.

Given the mild and wet conditions prevalent in Atlantic Canada, drought is considered a comparatively minor force of disturbance. However, although climatic conditions are expected to become wetter overall, drier springs and summers are predicted in some areas of Atlantic Canada. Compounding the problem of seasonal drought is the predicted shift in precipitation patterns, which may result in a greater amount of precipitation limited to fewer but more severe storms with longer periods of dry weather between.

Less than 1% of the total forested area of the Atlantic Canadian provinces was burned in 2005. Given the current direct contribution of fire to the overall disturbance regime of Atlantic Canada and the overall wetter conditions predicted for the region in a future climate (Flannigan et al. 2001), fire itself will not likely become a matter of increased concern. However, because disturbances are linked, the overall vulnerability of forests to fire in a changed climate may still increase. This increase in vulnerability will arise from the presence of large amounts of snags and downed logs as a consequence of increased insect outbreaks or windstorms combined with the increased potential of drought.

Acadian forests are subject to damage by wind, as illustrated by the swath of damage left across Nova Scotia and Prince Edward Island by Hurricane Juan in 2003 (Canadian Forest Service 2005). Wind is also a major disturbance regime in the forests of Labrador (Bergeron et al. 2002) and the island of Newfoundland. The predicted warming of the north Atlantic may result in an increase in the severity and frequency of severe weather (Peterson 2000). When this factor is combined with the overall predicted increase in wind speed, Atlantic Canadian forests will become vulnerable to large-scale windthrow, especially in coastal regions. The shallow-rooting tree species characteristic of Atlantic Canada are especially vulnerable to damage from heavy winds (Peterson 2000).

IMPACTS ON THE FOREST SECTOR

Thus far in this report the current, future, and regional relations between climate change and forest ecosystems have been considered. This chapter considers the impacts of climate change on the Canadian forest sector. Climate change is affecting or will have future effects on:

- forest management (e.g., timber supply and the ability to achieve forest management objectives)
- forest operations (i.e., the ability to provide a stable supply of quality raw material to mills at reasonable cost with minimal environmental impact)
- the forest industry (i.e., the ability to earn a competitive return on investment)
- forest-based communities (e.g., jobs, income, social well-being, social and cultural ties to surrounding forest landscapes) and
- the supply of forest-based public goods to Canadian society (e.g., wildlife habitat, special places, clean air and water, productive soils, biodiversity resources, recreation and tourism opportunities, and aesthetics) (Figure 3).

Impacts in these areas will vary in magnitude and direction depending on location and time horizon. Moreover, it is difficult to make precise and unambiguous predictions about impacts, especially about long-term ones. In fact, because uncertainty accumulates at each step, uncertainty about the impacts of climate change on the forest sector is higher than uncertainty about impacts on forest ecosystems. It is possible, however, to begin to make some general inferences about how climate change might affect Canada's forest sector and to begin to identify important implications for forest management and operations.

Forest management

Forest management in the context of public forest lands refers to the use, manipulation, management, and modification of forests and forest land to achieve social, economic, and environmental objectives. It generally includes aspects of forest inventory and mapping, growth and yield estimation, resource and timber supply analysis, harvest regulation, land and forest management planning, zoning, public consultation, maintaining environmental standards, valuation and trade-off analysis, reforestation and other silvicultural techniques, and forest protection. Climate change and the kinds of biophysical impacts described earlier will likely affect the ability of Canadian forest managers to achieve forest management objectives (Mote et al. 2003; Ogden and Innes 2007b). The implication is that forest management objectives and the means used to achieve them may need to be modified.

Most (94%) of the forest land in Canada is under public ownership. Concepts such as the allowable annual cut and the long-run sustainable yield provide ways to physically measure the timber supply. The annual allowable cut is a target harvest volume that is set to achieve land-manager objectives (including sustained yield). The determination of the allowable annual cut gives consideration to, and is a reflection of, multiple factors including socioeconomic factors, the amount of public forest land that has been set aside and designated as the commercial land base, the productive capacity of the commercial

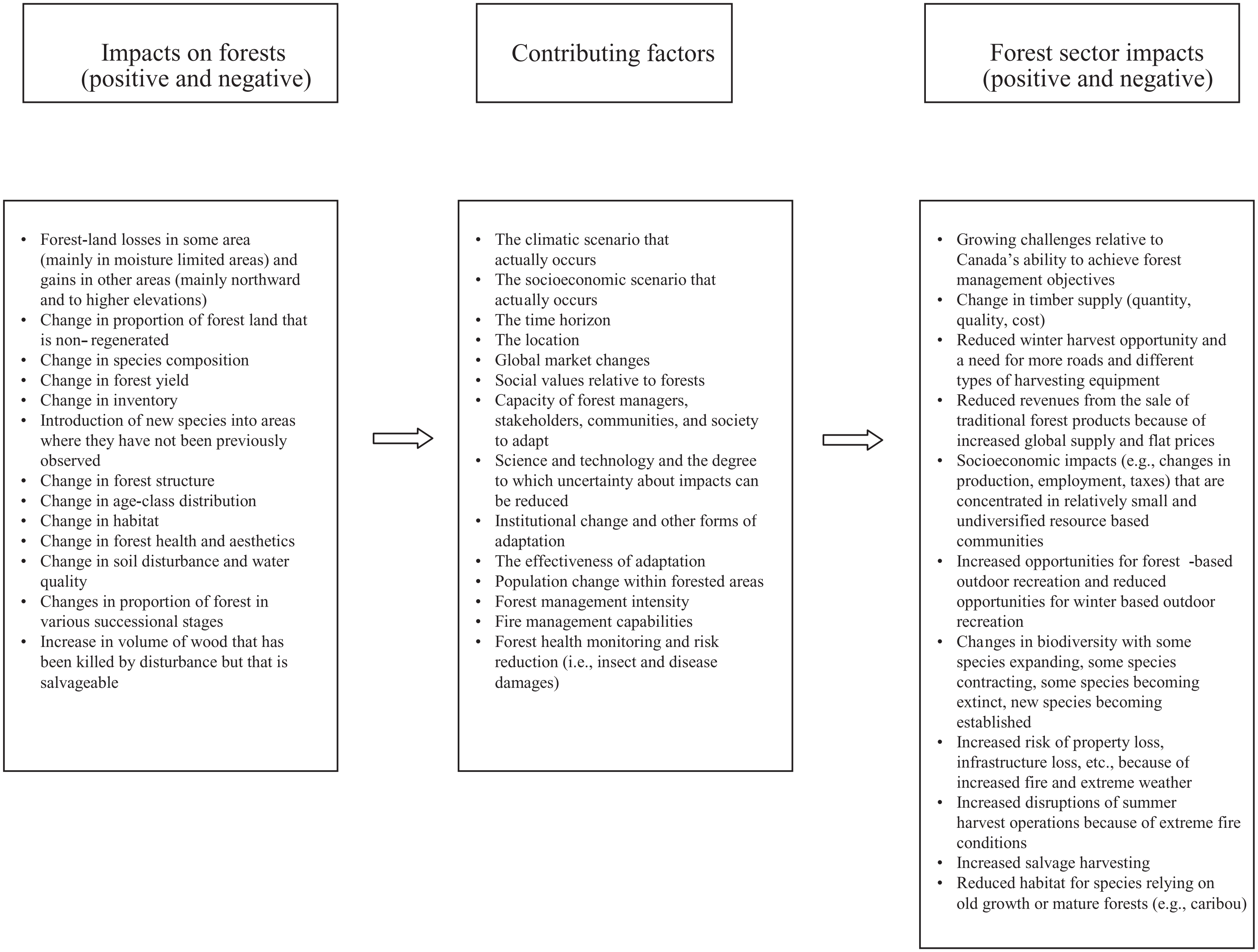

Figure 3. Climate change impacts on the forest sector.

KEY MESSAGES

TIMBER SUPPLY

- **Changes in timber supply may be positive or negative depending on location, time frame, and human adaptation to the effects of climate change.**
- **Regions that are currently hot and dry may experience a decrease in productivity and inventory in the near future.**
- **The magnitude of the socioeconomic impacts resulting from changes in timber supply will depend on how fast the changes occur.**
- **If the changes are gradual then forest managers will be able to adapt and adjust as new information becomes available.**
- **The most significant impacts will occur where changes in timber supply occur over a short time period. The current experience with the mountain pine beetle shows that this can happen.**

land base, the existing stock of forest inventory on the land base, expected losses through disturbance events, management inputs (e.g., reforestation, thinning, tree improvement), rotation age, and regulatory constraints (e.g., flow constraints). Measures of timber supply such as allowable annual cut and long-run sustainable yield are not static measures. They are modified and updated on an ongoing basis in response to updated information and in response to changes in land base, changes in resource priorities, unexpected disturbance losses, changes in productivity, and changes in accessibility (e.g., new roads) (Hauer et al. 2001).

Climate change has changed current timber supply and will continue to change it in the future. The net impact of climate change on timber supply in any particular timber-supply planning area will be determined by a number of other interrelated factors including the impacts of climate change on forest land area, growth, disturbance patterns, management inputs, regulatory constraints, regeneration success, and species composition. At local scales, changes in timber supply may be positive or negative depending on location, time frame, and human adaptation to the effects of climate change.

The magnitude of the socioeconomic impacts resulting from changes in timber supply will depend fundamentally on how fast these changes occur. Slow and gradual changes in timber supply will certainly be significant over time and they need to be considered today in forest management planning. However, if the changes are gradual then forest managers, the forest industry, and forest-based communities will probably be able to adapt and adjust. In the case of the industry, the key consideration is the degree to which changes in timber supply jeopardize fixed capital investments. If timber supply under climate change does not fall below the requirements of an existing mill over its life-span, then the net impacts may be relatively small (assuming that delivered wood costs do not increase significantly) because it will be possible to adjust and adapt technologies and capital assets to the new forest conditions.

The most significant socioeconomic impacts will be felt where changes in timber supply occur over a short time period. The experience with the mountain pine beetle in British Columbia shows that climate change factors can contribute to significant changes in timber supply in a relatively short period of time. For example, the allowable annual cut of the Vanderhoof Forest District in the Prince George Timber Supply Area has gone from its traditional level of around 2 million m^3 (around the year 2000) to its current level of around 6.5 million m^3 (to facilitate salvage of beetle-killed pine [Pederson 2004]). Under a worst-case harvest projection, the harvest in the Vanderhoof Forest District could potentially drop to about 1 million m^3 per year by 2020 (once the salvage phase is completed) and then gradually increase back up to 1.75 million m^3 over a 50-year period (Pederson 2004). Such large swings in local timber supply and the associated changes in production and employment compressed within a relatively short time frame can result in significant challenges to communities and forestry companies.

A second issue concerns the degree to which climate change affects Canada's ability to achieve objectives for sustainable forest management (Mote et al. 2003; Ogden and Innes 2007b). The Canadian Council of Forest Ministers has developed a framework that defines sustainable forest management and provides a basis for measuring progress toward sustainable forest management (CCFM 2006). The framework is based on six criteria, which represent important classes of values that Canadian society associates with forests and forest management:

1) biological diversity,
2) ecosystem condition and productivity,
3) soil and water,
4) role of forests in global ecological cycles,
5) economic and social benefits, and
6) society's responsibility.

The framework also includes a set of indicators or measures that assess Canada's performance in providing a socially desired level of benefits for each criterion.

Climate change, which is beyond the control of the Canadian forest management sector, has the potential to affect each of these classes of values (Ogden and Innes 2007b). For example, Criterion 1 (biological diversity) states that "maintenance of the natural range of ecosystems, and the ability of their components to react to external forces and processes, provides the equilibrium required for the maintenance of species diversity." However, as noted in previous chapters, climate change will likely exceed the ability of species to migrate and it will almost certainly result in disequilibrium and changes in the composition of forests and distribution of species over time. Therefore, maintaining current species and ecosystem configurations and age-class distributions will likely not be feasible under climate change (Hebda 1998).

Criterion 2 (ecosystem condition and productivity) states that "the sustainable development of our forested ecosystems depends on their ability to maintain ecological functions and processes and to perpetuate themselves over the long term." The Canadian forest sector may require some fundamentally new approaches to management if it is to achieve this objective. In particular it may require a management system that anticipates future conditions, encourages and facilitates the migration and movement of species and genotypes, and recognizes that ecosystems will be moving over time.

Criterion 3 (soil and water) states that "the construction of access roads and other forestry practices may impact on the quantity and quality of soil and water in a number of ways." However, as will be discussed in the next chapter, climate change is already resulting in shorter winter harvest seasons. This means that the forest industry may have to build more roads to stay in business. It also means that there is the potential for greater soil disturbance if harvesting takes place more frequently on unfrozen ground.

Criterion 4 (role of forests in global ecological cycles) states that "the indicators under this criterion deal with the role of forests and the forest sector in the global carbon cycle." Indicators of performance include measures such as net change in forest-ecosystem carbon. The long-term effects of climate change on sequestered carbon in Canada's forests are unknown. However, the expected increases in fire, insect, and disease disturbance have the potential to release into the atmosphere significant quantities of carbon that is currently stored in forest ecosystems (see for example Kurz et al. [2008]).

KEY MESSAGES

FOREST MANAGEMENT OBJECTIVES

- **Climate change will challenge our ability to achieve forest management objectives.**
- **The forest management sector should consider ways to begin incorporating climate change considerations into forest management objectives and the means that are used to achieve these objectives.**

The sensitivity of forests to climate change and the potential for widespread impacts on the array of goods and services that Canadian society derives from forests mean that climate change considerations should start to be incorporated into all aspects of forest management in Canada (Mote et al. 2003; McKinnon and Webber 2005; Lazar 2005; Ogden and Innes 2007b). One of the first priorities is to enhance our ability to estimate future impacts and incorporate these into timber-supply analysis and long-term plans. Second, because climate change has major implications for our ability to achieve forest management objectives as they are currently defined, the forest management sector will need to start reviewing those objectives as well as the means that it uses to achieve them. Ogden and Innes (2007b) provide a through overview of adaptation options that forest managers might consider (Chapter 6). Haley and Nelson (2007) identified ideal properties and attributes for redesigned tenure that would facilitate and enhance Canada's ability to achieve sustainable forestry, including social legitimacy, flexibility, transparency, security, diversity, cost-effective regulatory compliance, and efficient and equitable timber pricing.

Forest operations

Discussions with forest companies in Saskatchewan have indicated that changes to seasonal harvest operations are already becoming significant. During the winter of 2005–2006, frozen-ground conditions did not occur until after January 1. Harvest operations normally scheduled for frozen soils ("winter ground" includes wetter sites, sites that are prone to soil compaction, and sites that are inaccessible in summer) were reallocated to drier sites ("summer ground"). On the basis of future projections for warmer winters and more precipitation (note that early snows insulate the ground and limit freezing), it can be predicted that the time window when frozen-ground conditions exist will continue to shorten (Barrow et al. 2004).

KEY MESSAGES

FOREST OPERATIONS

- **Forest companies are already seeing the effects of climate change in the form of shorter winter-harvest seasons.**
- **The time window when frozen-ground conditions exist will continue to decrease in the future.**
- **Reduced winter-harvest opportunities may result in the need for more roads or the use of different types of harvesting equipment on sensitive sites, both of which may result in an increase in delivered wood costs.**

Output from the Canadian Regional Climate Model (Laprise et al. 2003) indicates that the proportion of frozen water in the upper 100 cm of soil will decline in the winter months by the 2050s. For the Mistik Management Forest Management Agreement area in northwest Saskatchewan, declines are projected to be about 10% each month from December to March and 30% in April (Johnston 2007). This is a potentially large problem in many boreal forest regions because some Forest Management Agreement areas may consist of up to 40% wetlands.

Forest companies require new adaptation options to deal with the decrease in frozen-ground conditions. In the short term, more harvesting can be done on summer ground, but eventually timber supply in summer-access areas will run out. Some have suggested building more permanent roads, but such projects are expensive. In addition, the current provincial forest management policy in many jurisdictions is to minimize permanent road construction and to rehabilitate temporary roads once harvest activities are complete. Specialized equipment (e.g., high-flotation tires) is available but expensive and can only be used for a short time each year. In addition, some of these technologies require additional maintenance. This also adds to costs.

Forest industry

The Canadian forest industry will potentially be affected by climate change through changes in the cost and availability of timber and changes in global markets (van Kooten and Arthur 1989). Earlier chapters discussed the implications of climate change for timber supply and forestry operations. This chapter discusses ways that the Canadian forest industry might be affected by changes in global markets.

Canada is the leading exporter of forest products in the world. Forest products are a major export commodity for Canada and thus of importance to the Canadian economy. Sohngen and Sedjo (2005) suggested that climate change will increase the global timber supply.

Forests in some regions of the world may decline whereas forests in other regions may increase. It is generally expected that there will be an overall increase in the global supply of forest products and a restructuring of the global trade in forest products. However, some countries will gain more than others and this will lead to shifts in the comparative advantages of exporting countries. Sohngen and Sedjo (2005) found that climate change will decrease the economic benefits (i.e., producer surplus) for North American producers. The decrease in benefits will be significant in the early part of the 21st century as a result of a decline in relative prices and in the relative market share held by North American producers. Producers in the southern hemisphere will benefit from climate change and will continue to do so throughout the 21st century.

> *...Canada's producers of forest products are uniquely vulnerable to market impacts relative to their counterparts elsewhere in the world.*

Perez-Garcia et al. (2002) provided country-specific predictions of the market impacts of climate change up to 2040. Of the countries included in the analysis, Canada is the only one for which the impacts on producers are predicted to be negative. Moreover, these negative impacts are predicted to be significant. In fact, the analysis suggests that Canada's producers of forest products are uniquely vulnerable to market impacts relative to their counterparts elsewhere in the world.

It is important to note that the market impacts are predicted to occur over a long time period. Moreover, the kinds of structural changes that are predicted to result from climate change will occur alongside a host of other changes that are simultaneously affecting markets for forest products. Technological changes, trade disputes, changes in exchange rates, interest-rate changes, and changes in consumer tastes and preferences are just a few examples of the changes that will be occurring at the same time as the market effects of climate change. It may, therefore, be difficult to isolate the effects of climate change from other market influences, and it may be difficult to develop and implement specific adaptation measures in response solely to the market impacts of climate change.

KEY MESSAGES

MARKET IMPACTS

- **Climate change may result in structural change in global markets for forest products, with producers in the southern hemisphere being the main beneficiaries.**
- **The impacts on North American producers of structural change in global markets as a result of climate change may be negative.**
- **The Canadian forest industry might consider a comprehensive strategy to position itself to address the combined impacts of climate change and other trends in global markets.**

Canada has relatively high labor costs and high wood costs. Canada's market share in traditional commodity lines has, in some cases, already started to decline for reasons unrelated to climate change. However, the countries whose products are replacing Canadian products in the global market are those that are expected to be significant beneficiaries of climate change (i.e., countries in South America and Oceania) (Perez-Garcia et al. 2002). Adaptation should, therefore, be based on consideration of the combined impacts of climate change and other market factors.

It may be necessary to increase the adaptive capacity of Canadian firms by identifying, removing, or reducing institutional barriers that limit Canada's ability to adapt and compete in global markets. Some specific areas that have been proposed include the following: taking measures to develop new value-added products, developing specialized niche markets, improving efficiency, and reducing costs. Each of these will require a strong commitment to technology development and innovation and a commitment to identify and reduce any institutional barriers that impede the ability of the forest industry to produce products at a competitive cost and to adapt and evolve in response to changing market conditions (Haley and Nelson 2007).

Forest-based communities

The impacts of climate change will not be evenly distributed across Canadian society. Some segments of Canadian society face higher risks because of their location, their association with climate-sensitive environments, and their economic, political, and cultural characteristics (Davidson et al. 2003; Williamson et al. 2007). Rural, resource-based communities are of particular concern (Standing Senate Committee on Agriculture and Forestry 2003).

Forest-based communities face the same kinds of impacts and risks associated with climate change that non-forest-based communities face. These include potential health effects, impacts on infrastructure, and exposure to extreme weather events. However, forest-based communities face a number of additional factors that contribute to their overall vulnerability to climate change (Williamson et al. 2007), including strong ties to the surrounding climate-sensitive forest landscape, increased risks owing to expected increases in wildfire activity (in some locations), changes in local wood supply, and changes in the relative competitiveness of local firms. These latter factors can have significant impacts on local economies, particularly in cases in which those economies are heavily dependent on the forest-products sector.

Davidson et al. (2003) identified five additional socioeconomic factors that contribute to the heightened levels of vulnerability of Canadian forest-based communities:

1) adaptive-capacity constraints (e.g., small and undiversified economies and overspecialized local labor forces with skill sets that are not transferable to other sectors);
2) the potential for larger scale institutional responses to environmental issues and climate change that ultimately affect small, rural, resource-based communities;
3) lack of consideration of climate change in forest management decisions and forestry institutions that may ultimately lead to higher impacts manifesting at the community level;
4) potential misperception of the risks of climate change; and
5) an increase in multiple, simultaneously occurring, and interacting risks.

The combined effects of higher potential impacts and lower adaptive capacity mean that forest-based communities tend to be relatively more vulnerable to climate change than other types of communities. The actual degree of vulnerability will vary from community to community. Nevertheless, systematic and structured assessments of vulnerability at a community level can help individuals and communities identify significant factors that are currently contributing to their vulnerability, or may do so in the future (Williamson et al. 2006). Williamson et al. (2007) described a framework and approach for assessment of vulnerability at the community level.

Williamson et al. (2008) developed methodologies for assessing local impacts and described the results of a case study assessing potential biophysical and socioeconomic impacts of climate change on a forest-based community in central British Columbia (the community of Vanderhoof). The Vanderhoof case study highlights areas and ways in which forest-based communities are uniquely exposed, sensitive, and therefore potentially vulnerable to climate change. Vanderhoof is currently being significantly affected by the mountain pine beetle outbreak in British Columbia. As indicated in an earlier chapter, this outbreak is partly due to recent climate change. The mountain pine beetle is having a major impact on the natural forest capital that to some degree supports the Vanderhoof economy. The immediate impact is a large increase in local harvesting to accommodate salvage of beetle-killed timber. However, harvest rates in the area are expected to decline below historical levels once salvage opportunities have ended.

For the longer term (i.e., up to around 2050), the study adopted a scenarios analysis approach and developed four scenarios of potential local impacts of climate change for Vanderhoof that are based on different assumptions about future climate and future socioeconomic conditions. The study found that in the longer term (up to 2050) forest cover will remain in the area and that productivity (and potential harvest) will actually increase under the climatic scenarios that could occur in Vanderhoof (although harvests are not expected to recover to the levels that occurred in the year 2000). However, fire risk in the Vanderhoof area is also expected to increase by 2050 and this may offset some of the expected gains in productivity. An additional risk factor for communities like Vanderhoof that are dependent on the forest industry could be reduced profitability in traditional commodity forest-products markets as a result of expected general increases in global timber supply under climate change (see previous chapter) and reduced opportunities for winter harvest.

The experience of Vanderhoof shows that the effects of climate change can be immediate and significant. A useful first step for communities is to assess how they are potentially vulnerable to climate change. Some of the key questions that forest-based communities might want to begin considering include the following:

- How has and is the local climate changing and what kinds of future changes in climate are expected in the local area?
- What are the potential implications in terms of extreme weather and in terms of other hazards such as forest fires and floods?
- Given the expected change in hazard risk, are local emergency preparedness measures adequate?
- What types of manufactured assets (buildings, equipment, infrastructure) and natural assets (forests, agriculture, water) currently support the local economy and how will these assets be affected by the changing climate and by the changing global economy?
- Can the community modify the mix of assets on which it depends to lessen its vulnerability to climate change (e.g., diversification, substitution of less vulnerable forms of capital for natural capital)?
- Does the community have sufficient capacity to adapt? How can the community strengthen its capacity to adapt?

Forest-based public and common-property goods and services

Provincial governments hold most of Canada's forest land (71%). The reason for retaining forests under public ownership is that Canadian society has determined that public ownership is necessary to provide an optimal level of social benefits and nonmarket goods and services (i.e., public goods and common-property goods)[1] from forests. Public and common-property goods and services associated with forests include clean air and water, productive soils, wildlife, protection and preservation of biodiversity, existence value (i.e., the knowledge that certain species or ecosystems continue to exist), bequest value (i.e., the knowledge that we are preserving natural capital for future generations), the provision of aesthetically pleasing vistas, and the provision of outdoor recreation opportunities. Forest-based public and common-property goods and services provided on public lands are vulnerable to climate change because these goods and services are closely linked to the health of forests and to the environmental services that forests supply.

KEY MESSAGES

FOREST-BASED COMMUNITIES

- **Forest-based communities may be more vulnerable to climate change because of their close association with climate-sensitive forest environments as well as their particular economic, social, political, and cultural characteristics.**
- **Factors such as small size, low economic diversity, and highly specialized labor forces may hamper the capacity of forest-based communities to adapt.**
- **Climate change has already affected communities in central British Columbia and it will continue to have effects for the next 50 years.**
- **An important first step for communities is to begin to evaluate how they may be vulnerable to climate change, including assessing exposure and sensitivity to climate change as well as their general capacity to adapt.**

Outdoor recreation and biodiversity are two important nonmarket forest-based products. Canadians spent 225 million days on various outdoor recreation activities in 1996 (Duwors et al. 1999). Forested ecoprovinces accounted for 195 million user days (86%) (Williamson et al. 2002). The main destinations for forest-based outdoor recreation were the Great Lakes – St. Lawrence ecoprovince and the South Boreal Shield ecoprovince. Outdoor recreation is sensitive to climate (Johnston et al. 2006). Browne and Hunt (2007) found that climate change will probably have a net positive effect on summer outdoor recreation activities because of lengthened season and higher temperatures. Winter-based activities, however, will decrease due to shorter seasons.

Ecological diversity encompasses species richness, genetic diversity, and the diversity of ecosystems (Gray 2005). Changes in ecological diversity will have important socioeconomic impacts. Many of the psychological non-use values of forests (e.g., option

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[1] Public goods are goods that are nonexclusive (i.e., the properties of the good are such that no one can be excluded from using the good) and nonrival (i.e., the properties of the good are also such that one person's use of the good does not reduce the amount available for a second person to use). A general example of a public good is police, ambulance, and fire services. Protection from crime, prompt medical attention, and reduced risk of major fire loss are equally accessible to all in a particular jurisdiction. Moreover, one person's use of these services does not reduce the amount that is available to another person. A common-property good is a good that is nonexclusive but rival in consumption. An example of a common-property good is wildlife.

value, bequest value, existence value, intrinsic value) are associated or closely aligned with biodiversity and ecological diversity (Hauer et al. 2001). It is expected that ecological diversity will change considerably over the next century in response to not only climate change but also human activities such as changes in and fragmentation of land use (Gray 2005). Varrin et al. (2007) considered the effects of climate change on representative species within Ontario. They noted that the risks of climate change for Ontario species will not be unidirectional but rather will vary by species, depending on species-specific traits and the nature of changes in interrelations between species. Risks will be the highest for species with small geographic ranges, with small populations, with specialized habitat requirements, with low genetic variability, with limited dispersal ability, and with a southern range boundary located in Canada. Although more research is needed, climate change may place additional pressure on species that are already endangered – such as woodland caribou.

CONCLUSION AND RECOMMENDATIONS

Growing awareness

Concerns about the effects of climate change on Canadian forestry began to be expressed in the 1980s. In recent years, awareness about climate change, concerns about the impacts of climate change on the forest sector, and recognition of the need to begin to incorporate climate change into decision-making have increased (Lemprière et al. 2008).

1) The Standing Senate Committee on Agriculture and Forestry noted that climate change will significantly affect agriculture, forests, water, rural communities, and Aboriginal people. They recommended increased research, improved communication, and tailoring of government programs to facilitate adaptation (Standing Senate Committee on Agriculture and Forestry 2003).
2) The Forest Products Association of Canada has noted that climate change "poses a significant risk to the health, vitality, and long-run sustainability of the forests and the many communities that depend on them" (Lazar 2005, page 631). The Forest Products Association of Canada calls for forest policies that balance the need to adapt to climate change with the need to mitigate factors that contribute to climate change.
3) The Government of Quebec recently announced a $6 million initiative to investigate the vulnerability of Quebec's forests to climate change.
4) The Chief Forester of the British Columbia Ministry of Forests and Range suggested that "resource managers have a responsibility to adapt forest management approaches to respond to environmental and ecological change" (Snetsinger 2006). The British Columbia Ministry of Forests and Range has responded with a number of initiatives to address and adapt to the impacts of climate change.
5) The Ontario Ministry of Natural Resources sponsors research focused on the impacts of climate change on forests and responsive adaptation strategies.
6) Forestry professionals have also started a dialogue about climate change. Articles or issues devoted to climate change can be found in *BC Forest Professional* (September–October 2006 issue), *Canadian Silviculture* (November 2006), and the *Forestry Chronicle* (Vol. 81, No. 5, September–October 2005). The Canadian Institute of Forestry's Position Statement # 4 calls for researchers and managers to work together to understand the impacts of climate change on Canada's forests and to develop strategies and approaches to reduce these impacts through adaptation (<http://www.cif-ifc.org/pdfs/policypos/E-Pos-4-Forests_Climate.pdf> accessed 24 Feb. 2007).
7) At the national level, the Canadian Council of Forest Ministers has identified climate change mitigation and adaptation along with transformation of the forest sector as "two priorities of national importance" for Canada's forest sector (CCFM 2008).

Characterizing the impacts of climate change on Canada's forests and forest sector

Climate change has certain characteristics that make it a unique and particularly challenging issue for the Canadian forest sector. First, the experience with the mountain pine beetle shows that large regional-scale impacts or events can occur. These events are usually the result of multiple interacting factors, only one of which may be climate change. Climate change may be a precipitating factor in changes in forest systems but in many cases it is not the sole factor. As illustrated by the mountain pine beetle issue, nonclimatic factors (e.g., past forest management practices, land clearing, fire suppression) can contribute to the sensitivity of forest systems to climate change. This illustrates the potential that may exist for reducing the possible impacts of climate change by taking preventive measures that reduce a system's sensitivity (or increase its resiliency) to the effects of climate change.

A second characteristic or feature of climate change is that managers will be required to manage forests within an increasingly complex, dynamic, and uncertain environment. Although there is a degree of certainty about climate change and its impacts at national scales there is significant uncertainty at the stand and forest level and this uncertainty increases with the length of the projection period. Stand- and forest-level projections and predictions about the impacts of future climate change are needed to guide local adaptation efforts, but any single prediction is subject to significant uncertainty and will likely be wrong (which is why it is necessary to use multiple projections or impact scenarios when assessing the impacts of future climate).

Uncertainty at the stand and forest level is largely due to the many interacting factors that ultimately contribute to particular types of impacts and the fact that uncertainty accumulates as one moves from climatic projections through to impacts on forests through to impacts on the forest sector. The degree of uncertainty also increases with the length of the prediction period.

Some managers may feel that impacts should be dealt with when they happen, not before they happen. However, uncertainty should not be used as an excuse for inaction. In some cases, delays might be warranted. In other cases, preventive measures may be required to reduce the risk of future large-scale impacts. A systematic assessment is required that considers the uncertainty of projections along with the potential costs and benefits of inaction versus action.

…uncertainty should not be used as an excuse for inaction.

If we are to address future climate change early action is needed. One option is to begin by assessing the vulnerability of forests and of the human systems that rely on or are closely attached to them. Other options include beginning to develop adaptation strategies and strengthening monitoring programs. The assessment of vulnerability and development of adaptation strategies are components of an iterative process; assessments and strategies must be revisited and updated as more knowledge becomes available.

The impacts of climate change will vary spatially and over time. Moreover, the impacts of climate change are not necessarily exclusively negative. In some locations there is the potential for increased productivity and for drawing higher value from forest resources. Adaptation can both reduce negative impacts and enhance positive impacts.

Adaptation

The rate of climate change that will be faced by Canada's forest sector and the consequent impacts have no historical analogue. Canada's forest sector will need to adapt (Lazar 2005; McKinnon and Webber 2005; Lemprière et al. 2008) and it will need to do so without the benefit of prior experience.

Adapting forest management to respond to climate change is starting to be recognized as a necessity (Lemmen et al. 2008; CCFM 2008). The benefits of adaptation include 1) exploiting opportunities, 2) reducing the potential negative impacts of climate change, and 3) reducing the risks associated with climate change. There are examples in Canadian forestry that show that the process of adaptation has already begun in a few isolated cases. For example, Millar Western Forest Products Limited in Alberta is investigating how to incorporate climate change into their long-term forest management planning (Yamasaki et al. 2008). As noted at the start of this chapter, a few provincial forest management agencies are beginning to consider their adaptation requirements and the British Columbia Ministry of Forests and Range is moving forward with an adaptation strategy. These are, however, preliminary steps and much more needs to be done to prepare for and adapt to future climate change.

> *…much more needs to be done to prepare for and adapt to future climate change.*

Although there is growing recognition of the need to adapt to climate change, there remains a degree of uncertainty about where and how to adapt. A useful first step would be to identify and better understand sources of vulnerability in forest ecosystems and the forest management system (Spittlehouse 2005, 2006, 2008; Lemprière et al. 2008). A forest management system that is vulnerable is one in which climate changes are expected to be significant, the forest management system is particularly sensitive to the kinds of climate changes that are anticipated, and the system has a relatively low capacity to adapt (Smit and Pilosova 2001; Johnston and Williamson 2007).

Even after sources of vulnerability have been documented, unexpected impacts will probably be experienced. Thus, in addition to the development of specific adaptation measures, there is also a need to enhance the general capacity of forest managers and forest management to adapt. Not only would this be of value with respect to climate change but also it would position the forest sector to address the full array of global, social, political, and economic changes that it faces. According to Smit and Pilosova (2001), core attributes of systems with high adaptive capacity include:

- an awareness of and an understanding of the urgency of the issue;
- a strong science capacity and access to technological options for adaptation;
- financial resources;
- effective institutions that are forward looking, flexible, and self-adaptive and that provide the authority for local adaptation to occur;
- high levels of human capital;
- effective networks and high levels of trust between various vested interests to facilitate information sharing and the development of collaborative solutions; and mechanisms for knowledge generation and dissemination and for the creation of tools and databases.

In terms of specific adaptation actions in the Canadian forest sector, Spittlehouse (2005, 2006, 2008) and Lemprière et al. (2008) described a number of requirements for adaptation to occur. Awareness must be increased and efforts must be undertaken to educate the forest sector about adaptation to climate change. Objectives must be established for the future forest under climate change. The vulnerability of forest ecosystems, forest communities, and society to climate change must be determined. Cost-effective actions for adaptation must be developed for the present and the future. The state of the forest must be monitored to identify when critical thresholds are reached. Finally, the forest must be managed to reduce vulnerability and speed recovery after disturbance.

Adapting to climate change will not be easy. We face a number of challenges to adaptation in the Canadian forest sector (Spittlehouse 2005). The first one is the generally high level of uncertainty about the direction, magnitude, and timing of future impacts of climate change (Spittlehouse 2005; Williamson et al. 2006). In a forest management context, there is a general lack of reliable prediction models and methods for forest management decision-making in the context of uncertainty about climate change. Effective adaptation will require the use of prediction models that estimate how forests will be affected by future climate change and how forests will respond to various adaptation measures. More attention needs to be paid to improving models for predicting the effects of climate change on future forest systems and to incorporating the results of these models into decision-support tools and forest management planning. However, there is also a need to acknowledge the limitations of models and to recognize that climate change will probably result in events that were not anticipated. Therefore, in addition to improving our predictive capacity, we should strengthen the forest sector's general capacity to adapt to unanticipated events (i.e., adaptive capacity), and its capacity to manage risk and make decisions when there is uncertainty (Ohlson et al. 2005). The capacity of forest managers to deal with the uncertainties associated with climate change will improve if their institutions are flexible, provide access to a diverse portfolio of prescription options, and promote adaptive management.

A second challenge related to enhanced adaptation in the Canadian forest sector is that there are institutional and policy barriers to adaptation; these must be reduced or removed. Most forest policies and institutions were designed and developed under the premise of a constant climate. Generally, there are no requirements or guidelines in Canadian forest management specifically designed to encourage adaptation to a changing climate (Spittlehouse 2005). Forest policies and institutions will need to be modified, or reengineered to accommodate climate change and to encourage adaptation. However, this will be difficult because forestry policies and institutions evolve slowly over time and they are based on historical experience. Resistance to change and reliance on historical experience ensure that forest policies and institutions provide stability and predictability. However, in order to encourage efficient and economically rational adaptation, forestry institutions and policies will need to be forward looking and flexible. The challenge will be to reengineer institutions and policy so that they efficiently allow for adaptation without sacrificing predictability and stability.

Many authors (Spittlehouse and Stewart (2004), Spittlehouse (2005, 2006, 2008), Ohlson et al. (2005), Johnston et al. (2006), Ogden and Innes (2007b), and Lemprière et al. (2008)) discuss various specific actions that the Canadian forest sector could take to adapt to climate change. Some illustrative examples are itemized in Table 1. Readers are encouraged to review the original articles for a more thorough discussion of adaptation options.

Conclusion

The purpose of this report is to raise awareness about climate change, its impacts on Canada's forest sector, and its implications for forest management and the forest sector in Canada. Canada's forest sector is experiencing and will continue to experience the impacts of rapid climate change. This has important implications for Canada's ability to manage forests in an economically and environmentally sustainable fashion. Ultimately, forest managers will need to adapt. The information presented in this report should help to inform the forest management community and contribute to a more constructive debate about adaptation requirements.

One strong finding is that we face significant levels of uncertainty regarding the impacts of future climate change. Uncertainty should not be a barrier or prevent adaptation, but it does make adaptation somewhat more challenging. Science can help to reduce this uncertainty over time. Climate change is fundamentally a scientific issue with very significant potential socioeconomic impacts and important policy implications. A stronger, better funded, and more focused science-based research effort will be required. However, this scientific effort cannot and should not proceed independently of the needs of policy-makers and forest managers. Mechanisms must be put in place to directly link science to policy, planning, and decision making.

Table 1. A summary of possible adaptation options for Canadian forest management

- Plant alternative genotype or new species in anticipation of future climate
- Agree on standardized climate scenarios for analysis
- Modify seed transfer zones
- Develop technology to use altered wood quality and size
- Be prepared to increase the amount of salvage logging
- Include climate variables in growth and yield models and incorporate climate change effects into long term timber supply analysis and forest management plans
- Incorporate climate change into land use plans and consider the possibility of land use change at specific locales (forest to agriculture and vice versa)
- Shorten rotation length
- Develop fire-smart landscapes and communities
- Plan landscapes to minimize the spread of insects and diseases
- Adopt risk assessment and adaptive management principles
- Diversify society's portfolio of forest assets
- Develop alternative harvesting systems and implement alternative harvesting practices
- Include climate change considerations when planning, constructing, or replacing infrastructure
- Prepare for variable timber supply
- Engage the public in a dialogue on values and management under a changing climate
- Maintain connectivity in a varied, dynamic landscape
- Monitor to determine when and what changes are occurring
- Redesign and or implement institutions that facilitate cost effective and economically efficient adaptation and that provide forest managers with the tools necessary to achieve forest management objectives
- Modify objectives for sustainable forest management and the means we use to achieve them
- Prepare for reduced winter harvest
- Prepare for increases in wildfire activity

Recommendations

Johnston et al. (2006) made five recommendations for positioning the Canadian forest sector to prepare for climate change, as follows:

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1. **Enhance the capacity to undertake integrated assessment of system vulnerabilities at various scales.**

Integrated assessments of vulnerabilities to climate change are required at multiple spatial and temporal scales and for various types of human systems. For example, an understanding of system vulnerabilities is required at national, regional, and local scales. Methods and approaches are required that consider the vulnerabilities of different types of human systems to climate change, including forest management systems, protected areas, programs, and forest-based communities.

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2. **Increase resources for impacts and adaptation science, and also increase resources to monitor the impacts of climate change.**

Climate change is a reality and it has major implications for the future state of forests. Foresters rely on prediction models (e.g., growth and yield and timber supply) to manage forests to achieve social objectives for public forests. In the past, historical data were used in estimating prediction models. This is no longer valid. Historical conditions are not representative of future conditions. Decisions made today that are based on expectations that future conditions will match historical conditions will likely fail. Thus, our success at managing forests depends on our ability to predict the future impacts of climate change on forests. However, the difficulty that forest managers face is that although climate change produces a greater need to predict the future (under changing conditions), it also produces greater uncertainty surrounding predictions of the future. Increased resources for monitoring the impacts of climate change and for adaptation research in the forest sector can reduce this uncertainty. More reliable prediction methods, lower uncertainty regarding predictions, and the ability to provide projections at scales relevant to decision makers will be essential if we are to develop efficient and effective strategies for adapting to climate change.

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3. **Review forest policies, forest planning, forest management approaches, and institutions to assess our ability to achieve social objectives under climate change.**

The Canadian forest sector has been hesitant to incorporate climate change into policy and planning. This may in part be due to the high levels of uncertainty that are associated with the future impacts of climate change, especially at the stand and forest levels.

Nevertheless, forest companies are already beginning to experience some impacts that may be related to climate change (e.g., a shorter winter-harvest season and the expansion of the mountain pine beetle's range). Moreover, the long growth cycles of trees put forest management in a unique position in terms of the need to include climate change considerations in current planning and decision making. Thus, consideration of climate change is not something that should be deferred in the forest sector.

There are a number of areas in which future climate change has important implications for current forest management. These are itemized as follows:

- There is a need to incorporate climate change into growth and yield forecasts.
- There is a need to incorporate climate change into long-term timber supply analysis and forest management planning.
- There is a need to incorporate climate change into reforestation choices.
- There is a need to consider climate change in identifying protection program requirements and in specific types of adaptations, such as reducing vulnerability by managing landscape configurations (e.g., "fire-smart" landscapes, insect-proofed landscapes).
- There is a need to incorporate climate change considerations into sustainable forest management objectives and into the practices that forest managers use or may use to achieve modified objectives.

A cumulative effects approach may, in some cases, be needed to determine appropriate actions. For example, some areas will be subject to increased risk of both drought and fire and therefore a shift in species composition toward more jack pine could provide multiple benefits.

4. Embed principles of risk management and adaptive management into forest management.

Climate change will increase the risk and uncertainty associated with forest management objectives. A change in risk may have implications for forest values and for choices made. It can be argued that the current approach to forest management is prescriptive and deterministic. A prescriptive and deterministic approach that is based on historical experience may be satisfactory when conditions are consistent but not when conditions are expected to change in multiple possible future directions.

Increased timber supply risk resulting from climate change has the potential to have real economic impacts and also to influence optimal harvest plans. Ignoring changes in risk from climate change will result in incorrect estimations of forestry benefits and suboptimal planning decisions. An important adaptation to climate change will be to account for and manage risk. Risk management strategies include risk prevention, risk reduction, risk spreading (e.g., insurance schemes), and portfolio diversification.

In addition to the need to manage risk, there is a need to be better prepared to deal with unanticipated and unpredictable events. The mountain pine beetle event, for example, was not anticipated and not predicted. Functional diversity, flexibility, management systems that recognize and account for uncertainty and unpredictability, and social structures that encourage adaptive management are important features in systems that are vulnerable to unpredicted and unanticipated events.

5. Maintain or improve the capacity for communications, networking, and information sharing with the Canadian public and within the forest sector.

Improving communications, networking, information sharing, collaboration, and cooperation is one way to effectively address the many challenges faced under a changing climate. Social capital is essentially the degree to which elements of a social system are networked and the degree to which constituents of the social system trust each other. Social capital provides individuals and groups with information and resources to which they might not otherwise have access. It contributes to resiliency and adaptive capacity.

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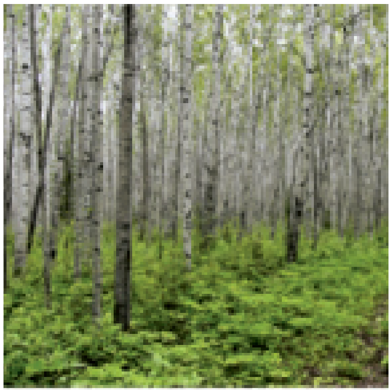


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