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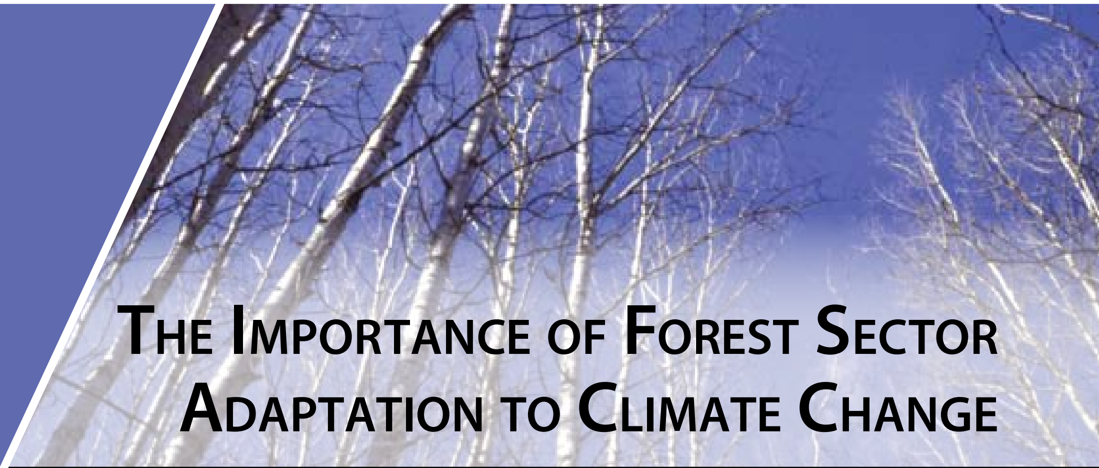

The Importance of Forest Sector Adaptation to Climate Change

T.C. Lemprière, P.Y. Bernier, A.L. Carroll, M.D. Flannigan, R.P. Gilsenan, D.W. McKenney, E.H. Hogg, J.H. Pedlar, and D. Blain

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Northern Forestry Centre
Canadian Forest Service

Canada

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The importance of forest sector adaptation to climate change

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ABSTRACT

This report summarizes current knowledge about recent changes in the climate of Canada's forests and projects further changes over this century based on scenarios of future global greenhouse gas emissions developed by the Intergovernmental Panel on Climate Change. Even with sustained reductions in global emissions the future climate is predicted to be quite different, meaning that adaptation will be essential. Impacts on the forest are already occurring and will be substantial in the future. The current upward trend in area burned annually is expected to continue. Forests will be prone to widespread stress induced by the changing climate, increasing the likelihood of pest outbreaks in the short to medium term. Recent outbreaks of several pests have exceeded in scope all previous known epidemics of these pests and are associated with the crossing of a climatic threshold. Invasion of the boreal forest by the mountain pine beetle, *Dendroctonus ponderosae* (Hopkins), appears likely, although the effect of this range expansion would likely be less severe than that observed recently in British Columbia, and outbreaks of the spruce budworm, *Choristoneura fumiferana* (Clemens), are predicted to be longer and more severe in the future. Future forest growth in response to climate change is expected to be variable, with growth reduction because of drought in parts of Canada's western forests perhaps the most dramatic short- to medium-term outcome, though modestly increased growth in the east is predicted. Such impacts have implications for the cost and characteristics of timber supply, and climate change will also affect forestry operations, recreation opportunities, biodiversity, and carbon storage. Planning based on past approaches will need to be reconsidered. Current objectives for sustainable forest management may not be attainable in the future, although there may be some new opportunities. Climate change may produce public safety risks, significant economic and social dislocation in forest-dependent communities including Aboriginal communities, and impacts on the competitiveness of companies as well as on the actions and policies of all levels of government. These effects can be reduced through early identification and implementation of actions to reduce vulnerabilities or take advantage of new opportunities. The key needs associated with adaptation in the forest sector include awareness building and debate, improved knowledge and information, vulnerability assessments, planning frameworks and tools, and enhanced coordination and cooperation among governments and other forest sector participants. Meeting the challenge of adaptation will require sustained effort for many years.

RÉSUMÉ

Le présent rapport résume les connaissances que nous avons à ce jour dans le domaine du changement climatique des forêts et projette les changements qui auront lieu au cours du siècle selon des scénarios développés par le Groupe d'experts intergouvernemental sur l'evolution du climat concernant les émissions de gaz à effet de serre dans le monde. Même si l'on réduit de façon constante au niveau mondial le niveau d'émission de gaz, on prévoit un changement climatique auquel il sera essentiel de s'adapter. On en voit déjà les répercussions sur les forêts et elles seront de plus en plus importantes. On s'attend à ce que la tendance actuelle de hausse de zones incendiées chaque année ne fasse qu'augmenter. Les forêts seront sujettes à des dommages étendus causés par le changement climatique, qui augmenteront la probabilité de pullulations de ravageurs à court et à moyen terme. Les pullulations de plusieurs ravageurs ont dépassé en envergure toutes les épidémies antérieures et sont associées au débordement du seuil climatique. L'invasion de la forêt boréale par le dendroctone du pin ponderosa, *Dendroctonus ponderosae* (Hopkins), commence, même si l'effet de cette aire de répartition serait possiblement moindre que celle observée en Colombie-Britannique, et on prévoit que les épidémies causées par la tordeuse des bourgeons de l'épinette, la *Choristoneura fumiferana* (Clemens), dureront plus longtemps et avec plus de sévérité. Sous l'influence du changement climatique, on s'attend à ce que la croissance des forêts soit variable, avec peut-être à court et à long terme, la réduction des forêts dans certaines parties de l'Ouest du Canada due à la sécheresse, alors qu'on anticipe une légère croissance dans l'Est du pays. De tels impacts ont des répercussions sur le coût et l'approvisionnement du bois d'œuvre et l'évolution du climat affectera également les opérations forestières, les possibilités récréatives, la biodiversité et la séquestration de carbone. La planification qui se basait sur le passé doit être évaluée de nouveau. Il se peut que les objectifs actuels concernant l'aménagement durable des forêts ne puissent pas être atteints dans le futur, même s'il existe de nouvelles opportunités. Il se peut que le changement climatique ait des conséquences sur la sécurité publique, provoque une rupture significative économique et sociale pour des communautés dépendantes des forêts comme celles des Autochtones, et qu'il ait un impact sur les capacités concurrentielles des compagnies et sur les actions et politiques à tous les niveaux gouvernementaux. Ces effets peuvent être réduits par une identification précoce et la mise en application d'actions qui réduiraient le niveau de vulnérabilité ou tireraient profit de nouvelles opportunités. Les éléments clés de l'adaptation du secteur forestier comprennent une prise de conscience et des débats, une amélioration des connaissances et de l'information, une évaluation des points vulnérables, une planification de cadres et d'outils et une augmentation de la coordination et de la coopération entre gouvernements et avec les autres intervenants du secteur forestier. Il faudra un effort continu pendant de nombreuses années pour relever le défi de l'adaptation.

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The Case for Adaptation

In its *Fourth Assessment Report*, the Intergovernmental Panel on Climate Change (IPCC) concluded that there is no doubt that the climate is changing and that there is 90% certainty that humans are the cause of climate change. The IPCC also made it clear that even strong actions to reduce global greenhouse gas emissions will not prevent the climate from continuing to change for many decades to come. Thus, adaptation must be part of the response to climate change: mitigation by itself is not enough.

Forests and other wooded land cover 40% of Canada's area, constitute a major economic sector, support hundreds of resource-dependent communities, and provide a variety of environmental services to Canadians. Canada's forest is already being affected by climate change, and projections suggest that the climate may be quite different in the future than it is today, especially in the northern regions and continental interiors where most of the forest is located. Some future impacts on the forest may be beneficial but many will not, and impacts will vary by location and over time. The full range of forest-sector participants and the benefits they obtain from the forest will be affected. By focussing on adaptation, the forest sector and its stakeholders can help ensure Canada's continued ability to reap benefits from its forests. Focussing attention now is important for several reasons. First, because of climate change, the forest sector is entering a period of increasing uncertainty and risk in which planning based on past forest dynamics and management approaches is not appropriate. Second, current objectives for sustainable forest management may not be attainable in the future; determining appropriate objectives in a changing climate requires debate. Third, climate change creates the risk of significant economic and social dislocation in forest-dependent communities and will affect the competitiveness of companies as well as the actions and policies of all levels of government. Fourth, public safety risks may increase as wildfires, storms, and floods increase in frequency and severity. Fifth, the impacts of climate change can be reduced if efforts to identify and reduce vulnerabilities or take advantage of changes are implemented.

The Canadian forest-products industry is already facing significant economic challenges, but if efforts to adapt to climate change are not pursued, the longer term health of the industry and forest-dependent communities could suffer. Awareness of climate change as a general issue is growing rapidly in the forest sector and some thinking about adaptation is occurring. For the most part the adaptation efforts to date have focused on improving understanding, providing education, sharing information, exploring adaptation needs, including consideration of climate change in planning processes, and increasing cooperation. Substantial planned and systematic on-the-ground adaptation actions have not yet occurred in response to future climate change, in large part because of the complexities and uncertainties involved. This report explains why adaptation efforts need to be strengthened.

What Do We Know about the Changing Climate?

Figure ES.1 shows the five forest regions that were used in this assessment. Table ES.1 summarizes projections of how six climate variables could change between the end of the 20th century (1961–1990) and the end of the 21st century (2071–2100) for the five forest regions. These variables were chosen because of their integral roles in forest ecosystem processes such as growth and disturbance.

Looking first at recent changes in climate, considerable variation has been observed since the mid-20th century across Canada's forested regions. Temperature increases generally have been greater in the west and north, with quite drastic changes occurring in the Boreal West, Montane, and Pacific regions. These regions also have shown strong asymmetry in their warming patterns, with winters warming more than summers. The pattern is reversed for precipitation, with the largest increases occurring

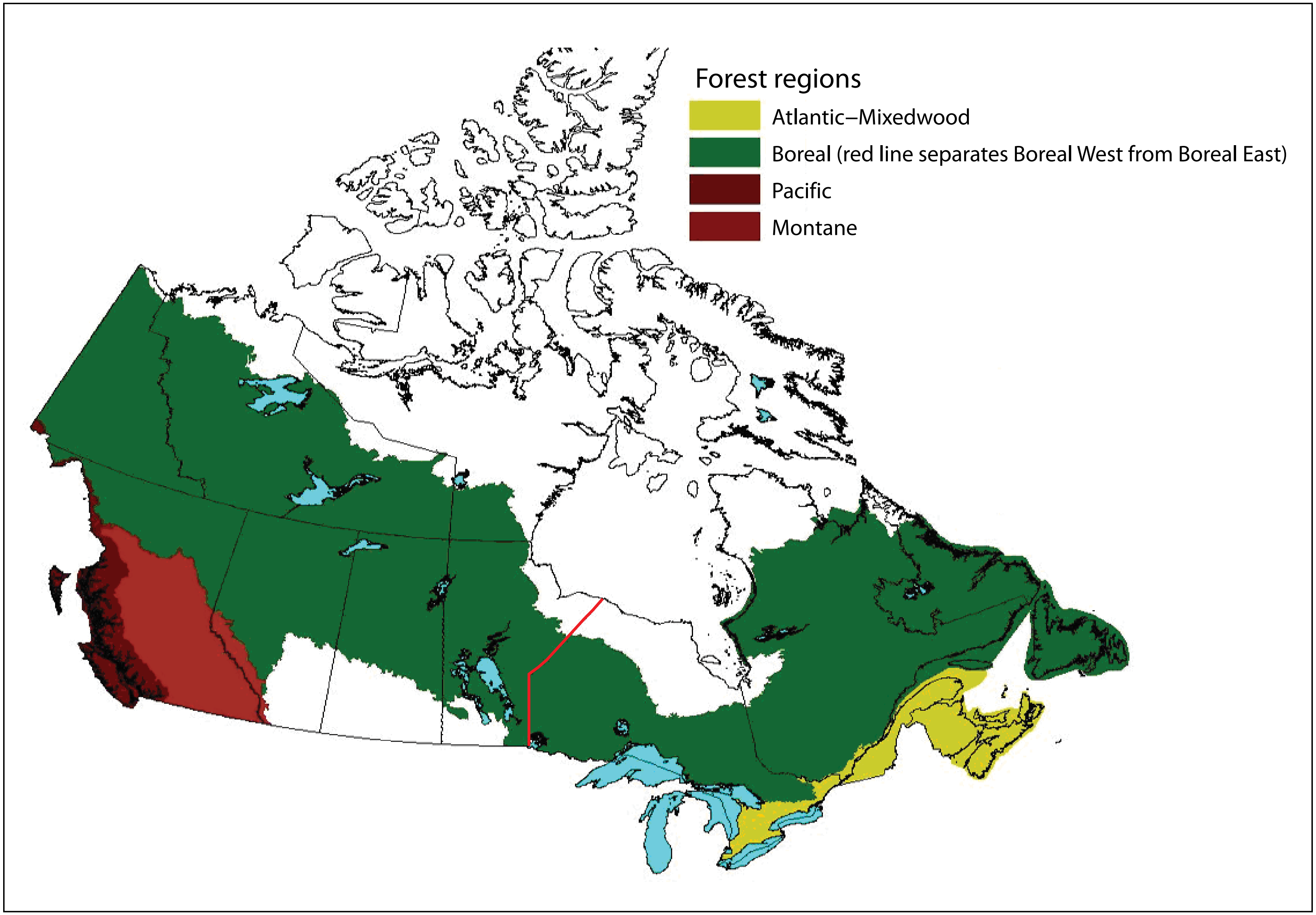

Figure ES.1. Forest regions used in this assessment.

Table ES.1. Estimates of change between 1961–1990 and 2071–2100 for climate variables. Projections for 2071–2100 are averages of 4 global climate model outputs for IPCC future global greenhouse gas emission scenarios A2 and B2. The values for Canada are based on the whole country, not just forested regions.

		Change between 1961–1990 and 2071–2100					
Region	Emission scenario[a]	Annual mean temperature (°C)	Maximum temperature of the hottest month (°C)	Minimum temperature of the coldest month (°C)	Degree days during growing season[b] (% increase)	Annual precipitation (mm)	Climate Moisture Index[c] (% change)
Atlantic–Mixedwood	A2	4.7	4.7	5.9	65	64	−18.0
	B2	3.5	3.4	4.8	46	59	−10.7
Boreal East	A2	5.3	4.8	7.8	96	93	−8.9
	B2	3.8	3.5	6.1	67	76	−4.2
Boreal West	A2	4.9	4.1	6.5	86	69	−37.4
	B2	3.6	2.9	4.5	61	57	−16.0
Montane	A2	4.1	5.0	4.4	104	63	−27.5
	B2	3.1	3.7	3.7	75	54	−17.1
Pacific	A2	3.7	4.1	3.5	92	107	0.8
	B2	2.8	3.1	2.7	66	65	0.3
Canada	A2	5.0	4.6	6.7	87	74	−19.2
	B2	3.7	3.3	5.0	61	61	−10.1

[a] Emission scenarios: A2 = scenario with a regionalized global economy in which the rate of increase in greenhouse gas emissions is comparable to the rate of increase in the 1990s. B2 = scenario with a regionalized global economy in which societies are more socially and environmentally conscious than in scenario A2, with slower population growth, lower energy intensity, and less reliance on fossil fuels, leading to a much lower rate of growth in greenhouse gas emissions.
[b] An indicator of total heat available for plants in the growing season.
[c] A measure of moisture available to plants throughout the year. A reduction indicates less moisture available.

in the east; western regions have shown little change or even a decline in precipitation levels in the case of the Pacific region. Over the last century most of southern Canada experienced significant trends toward fewer days with extreme low temperature during winter, spring, and summer and more days with extreme high temperature during winter and spring.

The projections for 2071–2100 used in Table ES.1 were derived by averaging the outputs from four general circulation models of climate for the A2 and B2 global greenhouse gas emissions scenarios developed by the IPCC. Neither scenario includes specific new efforts to reduce greenhouse gas emissions. The scenarios differ in that A2 assumes much higher population growth, slower convergence of incomes across countries and regions, less forested land, greater pollution, higher energy intensity, and greater reliance on fossil fuels than does B2. In 2000, global emissions were about 40 billion tonnes of carbon dioxide equivalents (this measure includes carbon dioxide, methane, nitrous oxide, and other more potent greenhouse gases). According to the IPCC, emissions under scenario A2 would be 250% higher by 2100 and the average global temperature would be 3.4 ºC higher (likely range of 2.0–5.4 ºC). Emissions under scenario B2 would be 75% higher than in 2000, with a temperature increase of 2.4 ºC (1.4–3.8 ºC). For both scenarios, warming is projected to be greatest over land and high northern latitudes, the location of Canada's forests.

Like any projection, climate projections contain uncertainties. The IPCC considers these two scenarios and others it uses to be equally sound: if emissions follow one of these paths, then the projected climate changes are likely to occur. We chose these two scenarios because we felt they represented plausible low-to-medium (B2) and high (A2) global emission paths over the next century in the absence of worldwide efforts to reduce emissions. In fact, although the A2 scenario could be perceived as relatively extreme, currently available evidence shows that carbon dioxide emissions have been increasing in recent years at rates higher than even those projected in the most pessimistic IPCC scenario.

However, it is also important to keep in mind that the scenarios used here do not take into account the potential for global efforts to substantially reduce emissions in the coming decades. One way to assess the implications of such efforts is to look at the IPCC's B1 global emission scenario. This scenario assumes a rapid change in economic structure toward a service and information economy and relatively rapid increases in the use of clean and resource-efficient technologies, although not as a result of new measures specifically aimed at addressing climate change. Under this scenario, emissions in 2100 would be about 40% lower than in 2000 but the global average temperature would still rise by 1.8 ºC (1.1–2.9 ºC), and the climate would continue to change beyond 2100. Increases could be higher in much of Canada's forested area. The IPCC suggests that a temperature increase of this magnitude would still cause considerable ecosystem change. Thus, forest sector adaptation would still be important.

An example of spatial and temporal detail is provided for projected changes in temperature in Figure ES.2. This time series of maps shows how annual mean temperature is predicted to change in the near future (2011–2040), medium term (2041–2070), and long term (2071–2100) on the basis of projections from a single general circulation climate model under the A2 scenario. According to these projections, increases of 3–5 °C would be common across the forested regions of Canada. The use of another model or emission scenario would yield different projected changes and spatial and temporal variations. However, different projections all tend to show that the greatest changes are predicted for northern Canada and the Prairies.

Annual precipitation is also predicted to increase in all forest regions over the course of the century under both the A2 and B2 emission scenarios. Despite these projected increases, however, available moisture (as estimated by the Climate Moisture Index) is expected to decrease in all regions except the Pacific region (Table ES.1) because the higher temperatures will lead to much greater rates of water loss by evaporation and transpiration. The impact of drying will be most noticeable in the western Canadian interior, where prairie-like moisture regimes are expected to expand northward to encompass large areas of the western boreal forest under the A2 scenario (Fig. ES.3).

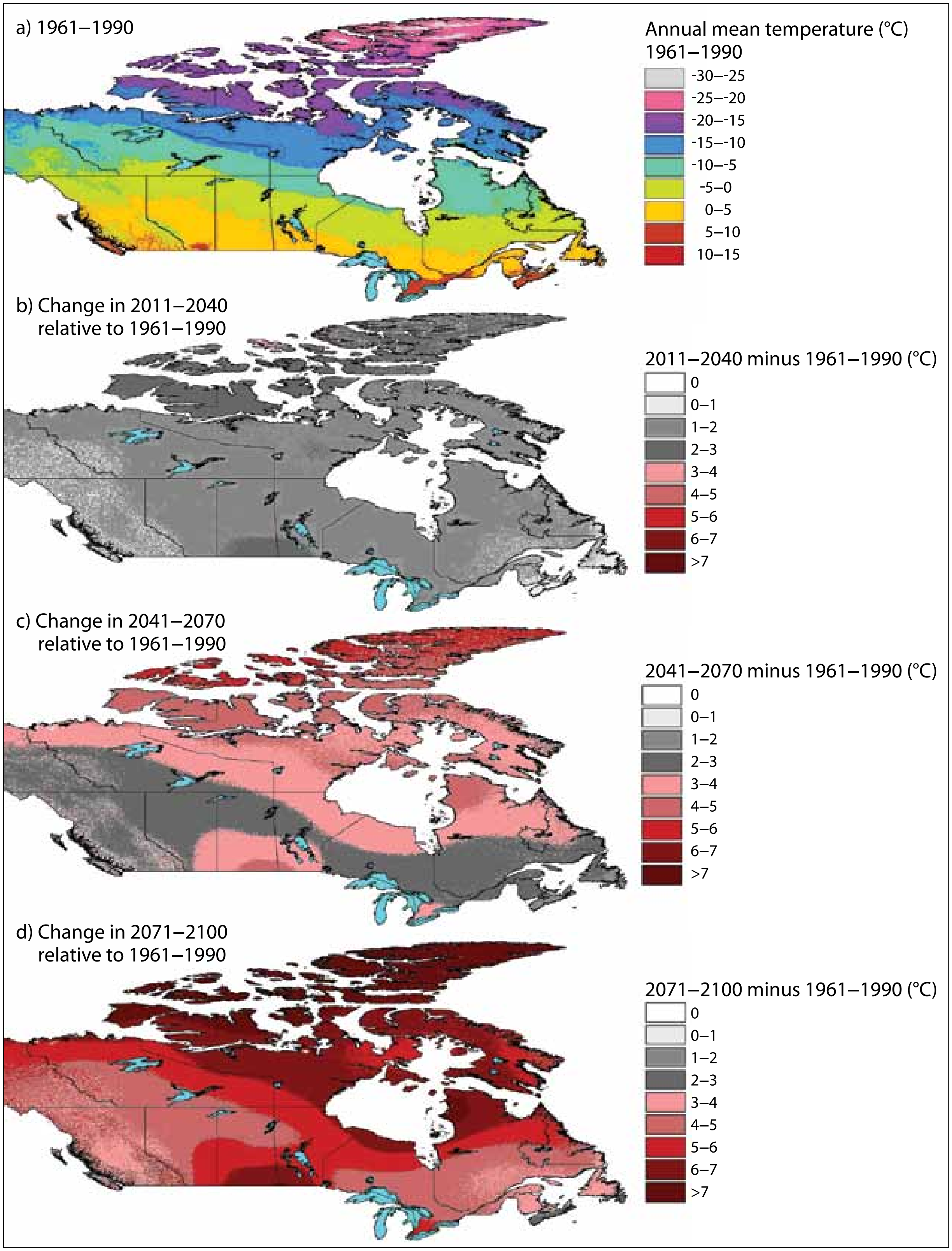

Figure ES.2. **An example of spatial and temporal variation in projected future changes (CGCM2–A2) in annual mean temperature for Canda.** a) Recent (1961–1990) annual mean temperature and change relative to 1961–1990 for b) 2011–2040, c) 2041–2070, and d) 2071–2100. CGCM2–A2 = Canadian Second-Generation Coupled Global Climate Model.

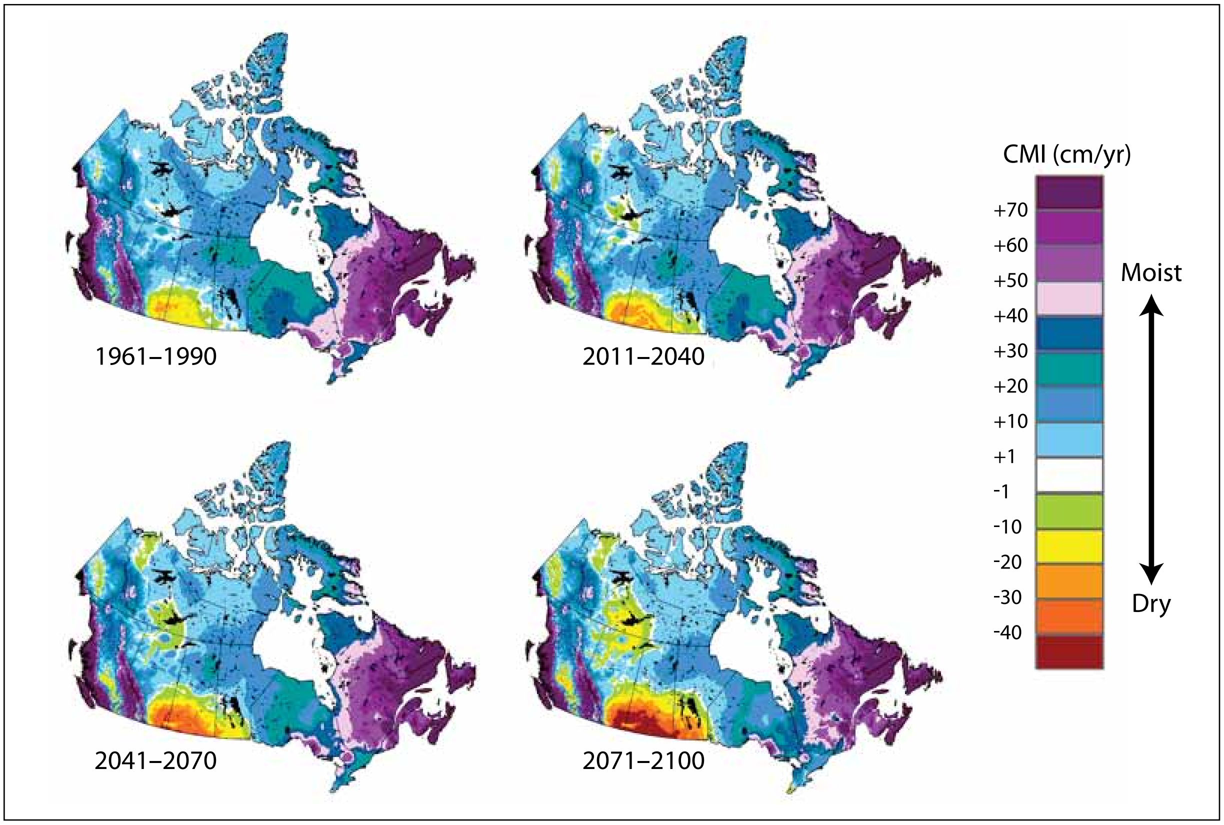

Figure ES.3. Historical and projected future (CGCM2–A2) moisture regimes based on the Climate Moisture Index (simplified Penman-Monteith method of Hogg [1997]). Negative values denote dry conditions typical of prairie or parkland climates. CMI = climatic moisture index, CGCM2–A2 = Canadian Second-Generation Coupled Global Climate Model with the A2 scenario in which the rate of increase in greenhouse gas emissions is comparable to the rate of increase in the 1990s. Maps by D. Price, M. Siltanen, and D. McKenney.

What Do We Know about how Climate Change Will Affect Forests and the Forest Sector?

Climate change will have a combination of effects on forest composition, productivity, and natural disturbances. The effects of the individual factors will interact in spatially and temporally complex ways, and at any given time or location they may be additive or offsetting. Other influences not related to climate change will also have an impact. Thus, integrated assessment is important for estimating the combined effects, but much more research is needed in this area. Determining how the forest responses then translate into impacts on human uses and forest values involves another layer of uncertainty. Table ES.2 summarizes the assessment in this report of the impacts of the changing climate on forests and forest values currently and over the next century. Such assessments become increasingly uncertain the further into the future one goes with these projections.

Table ES.2. Qualitative assessment of the impact of climate change on Canada's forests, timber supply, and forestry operations, by region

Period	Atlantic–Mixedwood	Boreal East	Boreal West	Montane	Pacific	Canada
Fire (size of area affected)						
Now	NC	++	+++	--	--	++
Near-term (2011–2040)	NC	++	+++	++	+	++
Medium-term (2041–2070)	+	+++	+++	+++	++	+++
Long-term (2071–2100)	++	+++	+++	+++	+++	+++
Biotic disturbance (considering size of area affected, severity, and frequency)						
Now	NC	NC	++	+++	+	+
Near-term (2011–2040)	+	+	+++	++	++	++
Medium-term (2041–2070)	++	++	+++	?	++	+++
Long-term (2071–2100)	?	?	?	?	?	?
Forest growth (productivity)						
Now	?	?	?	?	?	?
Near-term (2011–2040)	+	+	-	-	NC	?
Medium-term (2041–2070)	+	++	-	--	NC	?
Long-term (2071–2100)	+	++	--	---	NC	?
Timber supply (considering quantity, quality, and timing)						
Now	NC	+	+	+++	NC	++
Near-term (2011–2040)	+	-	+	+	NC	+
Medium-term (2041–2070)	+	-	--	--	+	-
Long-term (2071–2100)	+	-	-	-	+	-
Forestry operations						
Now	NC	-	-	---	NC	--
Near-term (2011–2040)	NC	-	--	-	NC	-
Medium-term (2041–2070)	+	-	-	+	-	-
Long-term (2071–2100)	+	-	-	+	-	-

NC = no change observed/expected. ? = uncertain. Scale of impact (increase/decrease for disturbances and growth, positive/negative for timber supply and forestry operations) is indicated as follows.
Increase/positive: + low, ++ moderate, +++ high. Decrease/negative: - low, -- moderate, --- high.

Natural Disturbances

Fire is the major stand-renewing agent for much of the Canadian forest, greatly influencing forest structure and function. Currently, an average of over 2 million hectares burn annually in Canada. There has been an upward trend in the area burned annually by wildfires since the early 1970s, with an increase in both the number of wildfires and the average area burned per fire. The trend is general but not uniformly distributed across the country: it is more pronounced in the western boreal and taiga ecozones (Boreal West region). Temperature is the most important predictor of area burned, with higher temperatures associated with increased area burned. Thus, recent climate warming can help to explain the increase in area burned. Further climate warming will lengthen fire seasons and increase seasonal fire severity ratings across Canada, suggesting that the average annual area burned will continue to increase in the future. Only a few studies have tried to quantify this; one study that used historical relations between weather (fire danger) and area burned in tandem with projections of future climate based on recent emissions trends found that the area burned could increase by about 74%–118% by roughly the end of the century.

Herbivorous insects, pathogens, and parasites are integral components of forests and some are capable of spreading over extensive landscapes and causing acute growth loss or mortality. Annually, the area of North American forests affected by these biotic disturbance agents is often many times greater than that affected by wildfire. The relation between climate and the abundance and distribution of these pests is complex, making it difficult to predict the effects of climate change on them.

Canada's wetter eastern forests have historically been more susceptible than other regions to large-scale infestations by pests such as the spruce budworm, *Choristoneura fumiferana* (Clemens). However, unprecedented insect outbreaks have recently occurred in western Canada; examples include outbreaks of the mountain pine beetle in British Columbia and Alberta, the spruce bark beetle, *Dendroctonus rufipennis* (Kirby), in the Yukon, and the dothistroma needle blight in northwestern British Columbia. Although these outbreaks vary in extent, they exceed in scope all previous epidemics caused by each pest species; involve native species or long-term residents of the areas where the outbreaks originated; and are associated with the crossing of a climatic threshold, in terms of either summer precipitation or winter temperature.

With respect to the future, some judgments can be made about the frequency and severity of biotic disturbances. First, for species found throughout their host-tree distribution (i.e., native ubiquitous species), a warming environment has the potential to affect the frequency, duration, and severity of disturbance events. Second, for species that are native but do not occupy the entire distribution of their host trees (i.e., native invasive species), climate change will potentially affect the range of the disturbances as well as their frequency, duration, and severity. Third, for species that are native but have historically not caused notable impacts (i.e., native innocuous species), changing climate has the potential to allow widespread disturbance. Fourth, for introduced species (i.e., alien invasive species), a warming environment may increase the probability of establishment. Projections have been developed for two major insect species: the spruce budworm (a native ubiquitous species), arguably the most significant pest in central and eastern Canada, and the mountain pine beetle (a native invasive species), the most significant pest of western pine forests. Under a scenario of relatively low global greenhouse gas emissions (i.e., lower than the B2 emission scenario), the resulting climate change is predicted to produce future outbreaks of the spruce budworm to 2081–2100 that will last an average of 6 years longer than they currently do and will cause 15% more defoliation. A climatic suitability model used in conjunction with projections of climate change indicates that Canada's boreal pine forests will become increasingly suitable for the mountain pine beetle in the near future. Thus, invasion of the boreal forest by the mountain pine beetle appears likely, although the effect of this range expansion would likely be less severe than that observed recently in British Columbia. Overall, it is very likely that there will be a short- to medium-term increase in the likelihood of biotic disturbance impacts, reflecting the fact that forests will be prone to widespread stress induced by climate change.

Response of Forests to Climate Change

Few generalizations can be made about the response of forest growth to recent climate change in Canada. Local and regional responses are probably driven by site-specific species and stand dynamics in addition to regional climate change, and both increases and decreases in forest growth have been observed. The productivity of the Canadian boreal forest has been decreasing recently, especially during 2001–2004, when droughts affected large areas. Future forest growth in response to climate change is predicted to be variable across the country and among species. The most dramatic short- to medium-term outcome is likely to be growth reduction owing to drought in many parts of western forests. In contrast, predictions typically call for modestly increased growth in the east. Altered species phenology (e.g., date of bud burst or leaf fall) and distribution are other forms of evidence of a changing climate. Because of the difficulty in detecting small changes in the context of large natural variability, the overall assessment is that it is very likely that climate change has had an effect on phenology but the effect has yet to be widely observed and recorded.

The generally accepted value of migration speed for tree species is 50 km per century. However, climate change may move isotherms (lines of equal temperature) northward by about 300 km within the next 50 years for most of Canada if annual mean temperature increases by 2 °C, with a corresponding northward move of climate-dependent suitability zones for tree species. This would outstrip the most optimistic estimates of the migratory ability of tree species. As a result, without human intervention, there will be a shift in dominance among the tree species already present within the forest rather than an invasion by new species. Large-scale disturbances will provide the most dramatic impetus for such changes in the species mix: under hot dry conditions, species such as aspen (*Populus* spp.) and birch that are able to regrow vegetatively following drought and fire may out-compete conifers, which reproduce through seed dispersal. Such local changes may occur very rapidly, over the course of a few decades.

Impacts of Climate Change on Human Uses and Nonmarket Benefits

The impacts described above have implications for the cost, quality, quantity, and timing of access to timber and the quantity and location of salvage. Future improvements in forest productivity could help to improve the long-term timber supply in some areas, but the impact of increases in disturbances on timber supply will dominate in most areas. Large natural disturbances, such as the current mountain pine beetle infestation, have the potential to temporarily create large amounts of salvage material. In turn this creates a host of challenges for infrastructure and forest management, including difficulties in accessing fallen timber, problems concerning industrial capacity and the technology needed to process the increased volume, transportation issues in terms of moving the large volume of dead or processed timber, and market access problems during high supply periods. A new set of difficulties would later occur as a result of subsequent local and regional shortfalls in timber.

Climate change will also affect forestry operations and practices such as timing of harvesting and road building. Shorter, warmer winters will reduce the life and usefulness of winter roads. A decrease in winter harvesting because of access problems, along with increasingly restricted summer harvesting owing to increases in fire danger, means a shorter harvesting period, a potentially reduced harvest, and significant increases in wood costs. Changes in the timing and volume of peak flow in streams (e.g., increased runoff) may cause road failures and affect other infrastructure such as buildings, which will in turn affect the practices used to build roads and other infrastructure.

In addition to timber, forests provide numerous nonmarket benefits to Canadians; they provide ecological, aesthetic, cultural, and heritage value. Parks and protected areas provide valued recreation opportunities and serve important conservation and heritage aims, but with climate change they may no longer fully encompass the ecosystems they were established to represent. The duration of recreational seasons will change,

with winters becoming shorter and summers longer, which could have positive or negative impacts on tourism and recreation depending on the location and types of activities affected. Forest ecosystem services provided by Canada's forests will be affected, including air and water purification, medicinal plants, nutrient cycling, and erosion control. The diversity of tree and other species in Canada's forests will be affected: for example, species that do relatively well in fire-dominated landscapes will become more common, especially jack pine (*Pinus banksiana* Lamb.) and aspen. In general, loss of biodiversity, where it occurs, would adversely affect the ability of forest ecosystems to absorb the impacts of subsequent changes without a fundamental disruption of their structure or functioning. The implications of climate change for forest carbon stocks are also worth noting. It is likely that increased natural disturbances will drive a period in which forest carbon stocks decrease and greenhouse gas emissions increase in the forest.

All of the above could profoundly affect the economic base of communities that are dependent on forest resources, including Aboriginal communities. As well, increases in the frequency and severity of fires, droughts, and biotic disturbances will very likely increase risks to public safety and personal property. Tourism and the cultural and aesthetic values attached to forests will also be affected.

What Is the Range of Adaptation Needs?

Climate change poses significant challenges for the sustainable management of Canada's forests in the coming decades. Adaptation to climate change occurs autonomously in natural systems. From the perspective of management, however, adaptation involves deliberate efforts to moderate potential damages or to benefit from new opportunities. Adaptation has a cost, but it is a key part of an economically efficient response to climate change.

The most significant challenge to adaptation is uncertainty, but that is not a reason to avoid careful thought and action. There is uncertainty about how the climate will change, especially at the local and regional level, which is compounded when one considers the impacts of climate change on the forest and the forest's potential future state, the degree to which the forest is vulnerable to climate change, and whether management objectives are appropriate or even feasible. Moreover, the impacts of changing climate will occur in the context of other uncertain future changes. Uncertainty is inherent in any planning for the future, but for the most part forest management decision-makers traditionally have assumed that current conditions will continue, and they do not take climatic or ecological uncertainty into account to any significant extent. With climate change, the assumption that current conditions will continue becomes increasingly questionable the further into the future one's projections go. Thus, adaptation will require explicitly integrating increased uncertainty into decision-making at all management levels.

Awareness of climate change as an issue has grown rapidly in the forest sector, helped by the publication of a number of assessments of its impacts and adaptation needs in recent years and ongoing research by federal, provincial, and university scientists. The Canadian Council of Forest Ministers has initiated discussion of what climate change means for Canada's forest and forest sector, and at its 2007 meeting the council identified adaptation to climate change as an emerging strategic issue for the sector. Provincial and territorial governments are taking action by developing strategies to address climate change, supporting research into climate change, and making efforts to increase awareness of the need for adaptation. Regional workshops have been held to explore the impacts of climate change on the forest sector and options for adaptation in specific contexts. Some assessment has occurred at the level of individual forest-based communities, and a few companies have tried to incorporate climate-change considerations into their forest management plans.

Numerous adaptation actions specific to the forest have been suggested at varying scales from local to regional to national. Identification of adaptation needs and selection of the actions to be undertaken will occur best when a systematic approach to adaptation decision-making is used, but as yet there is not a widely established framework for doing so. A structured risk management approach to adaptation would involve several steps.

First, management objectives must be set that will be appropriate for the forest in the future and that adaptation actions are meant to meet. The objectives could be based on existing criteria and indicators of sustainable forest management, but it must be recognized that current objectives may not be realistic in a changing climate. A focus on maintaining or increasing the resiliency of the forest in the face of climate change could be needed.

Second, current and future vulnerabilities that impinge on achieving the objectives must be assessed. This process is key for adaptation decision-making. Vulnerability is the extent to which a system is susceptible to damage. A system can be vulnerable at any scale from local to regional to national. A system's vulnerability depends on the degree to which it is exposed to climate change, the degree to which the objectives that have been set for the system and the values that are attached to the system are sensitive to this exposure, and the system's capacity to adjust or adapt. Adaptive capacity is determined by the characteristics of the sector and its participants. Adaptation can be thought of as making choices to reduce vulnerability by reducing sensitivity, facilitating or increasing adaptive capacity, and capitalizing on opportunities.

Third, adaptation strategies must be developed to address vulnerabilities or take advantage of opportunities. These strategies should recognize cumulative impacts, risk and uncertainty, and the varying needs of different stakeholders. They should also seek synergies with mitigation actions where possible. Mainstreaming is important: the most effective and successful adaptation will result from systematic integration of climatic considerations into existing forest planning and decision-making frameworks. Proactive strategies are probably better than reactive approaches because there may be a better chance that negative impacts and vulnerabilities can be avoided or reduced.

Fourth, adaptation strategies must be evaluated, decision-makers must decide which actions to take, and then the chosen strategy (or strategies) must be implemented and monitored. Multiple decision criteria can be used to evaluate alternative adaptation strategies and the trade-offs among them. These include criteria related to uncertainty, economic criteria including efficiency and impact on competitiveness, social criteria such as equity and social impacts, and environmental criteria. Adaptation decision-making will be strengthened if the range of forest sector participants is involved at all stages of adaptation planning. Different participants will have varying levels of knowledge, different perspectives, and different goals.

This report suggests that the forest sector has the following adaptation needs:

- A need for awareness and debate
  - Awareness building and education about climate change, risks, the need for adaptation, and potential options and strategies
  - Debate about objectives for future forests, including values, expectations, and goals and how climate change affects them
- A need for improved knowledge and information
  - Continued and expanded research on climate change and its impacts
  - Improved climate-monitoring records and expanded climate monitoring in northern and high-elevation forested areas
  - Accessible regional scenarios of future climate change that reduce uncertainties about what might happen where and when
  - Enhanced monitoring programs and systems to provide early notice of changes in the forest in response to climate change
  - Assessments of the potential impacts of climate change on carbon stocks, habitat, and biodiversity as well as other ecological benefits, including parks and protected areas
  - Scenarios of the impacts of climate change on timber supply and implications for use of salvage, product markets, mills, and communities

- Scenarios of the impacts of climate change on the competitiveness of Canada's forest-products industry
- Assessment of other social and economic impacts of climate change, such as its effects on Aboriginal communities
- Identification of viable options for adaptation (including their costs and the uncertainties associated with them) that address various objectives, such as maintaining habitat and biodiversity, assisting forest regeneration, optimizing forest products, or managing the forest to optimize its contribution to climate change mitigation
- Pilots and demonstrations that provide on-the-ground experience

- A need for vulnerability assessments at scales relevant to decision-making
  - Robust vulnerability assessment tools usable in a range of circumstances
  - Determination of the adaptive capacity of sector participants and assessment of lessons from current examples of adaptation to disruptive events
- A need for planning frameworks and tools at scales relevant for proactive adaptation planning and decision-making by a variety of sector participants with different objectives
  - Operational-level tools, such as climatically based models of growth and yield
  - Techniques for understanding and incorporating uncertainties and risk into ongoing forest sector decision-making (e.g., by fostering adaptive management)
  - Frameworks for understanding how current forest policies, regulations, and practices could change to increase the flexibility of responses without compromising future responses
- A need for coordination and cooperation, which will help meet the above needs more efficiently
  - Increased mechanisms for communicating, working together, and sharing information, knowledge, and experience

Perhaps the most important adaptation need is the need for debate about what climate change means for the values we derive from the forest, because climate change has the potential to affect all these values. It is unlikely that adaptation can be undertaken to address all the potential impacts of climate change, and in any case there is no reason to expect that adaptation will fully preserve the values on which we choose to focus. Our demands for forest goods and services will need to be revised in line with what adaptation is feasible and what new opportunities emerge.

Meeting the challenge of adaptation will require sustained effort for many years. The relatively small changes in climate in recent decades have already had an appreciable impact on the forest, and although there are uncertainties about the nature, location, and exact scale of future impacts, there is no doubt that there will be impacts. Even if global efforts to substantially reduce emissions in coming decades are successful, they will not prevent some degree of continuing climate change nor will they remove the need for adaptation to these changes.

1. WHY IS IT SO IMPORTANT FOR THE FOREST SECTOR TO ADAPT TO CLIMATE CHANGE?

There is no doubt that the climate is changing. The Intergovernmental Panel on Climate Change (IPCC) has concluded that this is the case and that there is 90% certainty that humans are the cause (Solomon et al. 2007). The IPCC has also made it clear that even strong global actions to reduce greenhouse gas emissions will not prevent our climate from continuing to change to some degree for many decades. Thus, adaptation must be part of the response to climate change: mitigation by itself is not enough (Parry et al. 2007; Lemmen et al. 2008). Countries around the world have recognized the reality that although global efforts to reduce emissions will continue to be needed for decades to come, substantially increased efforts to adapt to climate change are also required. The best actions will be those that contribute to both mitigation and adaptation at the same time.

Forests and other wooded land cover 40% of Canada's area, constitute a major economic sector, support hundreds of resource-dependent communities, and provide a variety of environmental services to Canadians. Projections suggest that the climate in Canada's forest will be quite different in the future than it is today, especially in the northern regions and continental interiors where most of the forest is located. Some impacts on the forest may be beneficial but many will not, and impacts will vary by location and over time. There will be changes in forest productivity, the length of the growing season, the frequency and severity of drought, and fire and pest disturbance regimes. In fact, Canada's forest ecosystems are already being affected; for example, drought-related dieback has occurred in some areas. There is strong evidence that forest fires have increased in frequency and size over the past few decades in parallel with changes in climate. Climate change also has contributed to outbreaks of the mountain pine beetle and other pests, and is removing climatic barriers to invasions by pests from warmer climates.

The full range of forest sector participants will be affected by such changes: governments, industry, and forest-dependent communities, including Aboriginal communities. Timber and wood processing, recreation, parks, and ecosystem benefits such as biodiversity and carbon recycling will be affected. If the forest sector and its stakeholders do not focus their attention on adaptation now, Canada's future ability to benefit from the forest may be compromised. There are a number of reasons why immediate attention is needed. First, because of climate change, the forest sector is entering a period of increasing uncertainty and risk in which planning based on past forest dynamics and management approaches will be increasingly inappropriate. Moreover, forest management decisions often have long-term consequences that cannot be reversed easily. Second, current objectives for sustainable forest management may not be achievable in the future. Determining appropriate objectives in a changing climate requires education, public debate, and dialogue. Third, climate-induced changes in timber supply, recreational opportunities, and other values derived from the forest create the risk of significant economic and social dislocation in forest-dependent communities. The competitiveness of companies will be affected, as will be the actions and policies of all levels of government. Fourth, risks to public safety may increase as wildfires, storms, and floods increase in frequency and severity. Fifth, the impact of climate change can be reduced if efforts to identify and reduce vulnerabilities or to take advantage of changes are implemented over time. Planned proactive action to address vulnerabilities and make adaptation to climate change a consideration in all decision-making (an approach known as "mainstreaming") is likely to be the most cost-effective and successful approach. By coordinating their efforts and learning from each other's experiences, forest sector stakeholders can help to lower the cost of adaptation.

The Canadian forest-products industry is currently facing significant challenges because of changes in global markets, timber supply, exchange rates, and costs; these changes are having profound impacts on competitiveness and employment and can mean that thinking about longer term adaptation to climate change is not a priority. However, if efforts to adapt to climate change are not pursued, it is likely that the longer term health of the industry and the communities that rely on it will suffer. The key to successful adaptation is to think about how to build adaptive capacity and increase flexibility to respond to climate change and other issues that affect the forest sector.

Governments, industry, and communities have begun to consider adaptation. This report provides a clear basis for understanding why these efforts need to be strengthened. The next section begins with a scientific assessment of knowledge about how recent climate change has affected Canada's forest. It then assesses how climate in the forest could change during the 21st century, on the basis of IPCC greenhouse gas emission scenarios, and also examines the potential impacts on the forest and forest sector if no adaptation were to occur. The third section of this report summarizes the status of adaptation by the forest sector and describes the key needs of the sector if it is to make progress on adaptation: awareness building and debate about what climate change means for society's objectives for the forest, improved knowledge and information about climate change and its impacts, vulnerability assessments, planning frameworks and tools, and coordination and cooperation in adaptation activities. Meeting the challenge of adaptation will require sustained effort for many years. The report concludes with a brief discussion of the potential roles of various participants in the forest sector in these efforts.

2. WHAT DO WE KNOW ABOUT THE CHANGING CLIMATE AND ITS IMPACT ON FORESTS?

Climate change will have a combination of effects on Canada's forests. It will affect forest growth and succession, fire activity, and insect and other biotic disturbances. However, untangling complex systems of biophysical interactions and predicting their responses to a changing climate at a time scale meaningful for forest management poses a daunting scientific challenge. Stand dynamics, disturbance regimes, and extreme climatic events interact to create complex landscape patterns. For example, the relation between the age and composition of stands and outbreaks of the mountain pine beetle, *Dendroctonus ponderosae* (Hopkins), is well established (e.g., Shore et al. 2000), and Gray (2008) estimated that forest composition exerts as strong an influence as climate on the dynamics of spruce budworm, *Choristoneura fumiferana* (Clemens), outbreaks. Recent studies have shown the spatial and temporal connection between different disturbance types and the greater vulnerability of weakened stands to disturbances. In Ontario, Fleming et al. (2002) observed that climate exerts a statistically significant control over the time lags between defoliation by spruce budworm and subsequent fires, with wetter areas less likely to experience a fire after defoliation than drier areas. In the Prairie provinces, drought and defoliation by the forest tent caterpillar, *Malacosoma disstria* (Hübner), have led to periodic collapses in the growth of aspen (*Populus* spp.) forests (Hogg et al. 2005), and the weakened stands are more susceptible to further damage by fungal pathogens and wood-boring insects (Hogg et al. 2002).

Thus, as a changing climate alters growth and succession processes it will also change a forest's vulnerability to insect outbreaks, which in turn will alter fuel loads and the probability of fires. Similarly, as a changing climate changes the frequency and intensity of fires it will also alter the forest's vulnerability to insect outbreaks. The effects of individual factors will interact in a spatially and temporally complex fashion, and at any given time or location they may be additive or offsetting. Estimating these joint effects is essential if we are to estimate the net effect of climate change on the forest. Ignoring the joint

effects could result in estimates as inaccurate as those that would result if we ignored one of the individual factors.

This section presents a synthesis of current understanding about how climate has changed to date and how it will change in the future and the impacts of these changes on forests and the forest sector. Information is synthesized for all of Canada's forests but is summarized for five regions that reflect major differences in forest type (Fig. 1). References to ecozones are also made (see the ecozone map in Appendix 1).

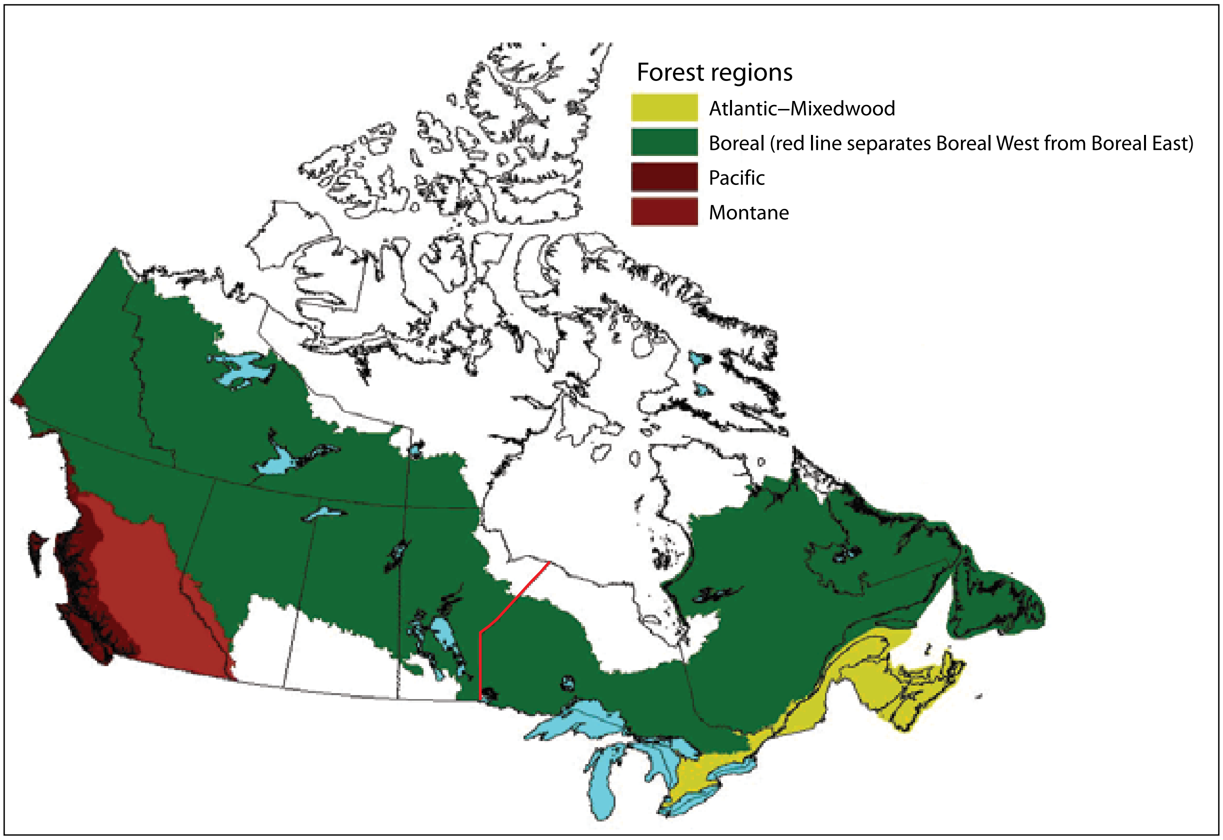

Figure 1. Forest regions used in this assessment.

Where appropriate and possible, qualitative assessments of uncertainty based on the scientific literature and expert judgment are provided in this section. Given the complexity of assessing climate change and its potential impacts and especially of projecting many decades into the future, it is difficult to assess the degree of uncertainty in general assessments. However, doing so provides important context. Uncertainty has a variety of causes (IPCC 2005). One is the unpredictability of the phenomenon under study, resulting, for example, from the complexity of interactions between the various factors contributing to the phenomenon or from a focus on projections. The further into the future a projection extends, the more uncertain it is. A second cause of uncertainty is a lack of complete understanding (structural uncertainty): this may be the cause of uncertainty that is most difficult to estimate, because the extent to which understanding is incomplete may not be realized. Finally, estimates, observations, and model results typically have inaccuracies. Several approaches can be used to convey probability or level of confidence (see IPCC 2005). In this section, assessments of likelihood are used to convey judgments about the degree of uncertainty associated with a conclusion or prediction: very likely (>90% probability), likely (>66% probability), about as likely as not (33% to 66% probability), and unlikely (<33% probability).

2.1 What Is Happening Now?

2.1.1 How Has Climate Changed?

Atmospheric concentrations of greenhouse gases have increased markedly over the past century owing primarily to human use of fossil fuels and land-use change (Solomon et al. 2007). Many studies have documented a coincident change in climate over this period at both global and regional scales. Here we provide summary climate trend information for Canada's forested regions for the period 1950–2003.

We made use of spatial models described in detail elsewhere (McKenney et al. 2006a). Briefly, climate station data (minimum temperature, maximum temperature, and precipitation) were obtained from Canadian and US sources for each month for the period 1950–2003. Spatial modelling software (ANUSPLIN; Hutchinson 2004) was then used to interpolate climate station data to produce maps for each month. From these maps of primary climate variables a further 29 annual bioclimatic indices were derived (see Appendix 2), five of which are presented in Table 1 in the present report: annual mean temperature (AMT), maximum temperature of the hottest month (MAXTHM), minimum temperature of the coldest month (MINTCM), annual precipitation (ANNP), and degree-days during the growing season (DDGS), which is an indicator of total heat available for plants in the growing season. These variables were chosen because of their integral roles in driving forest ecosystem processes such as growth and disturbance.

The extent to which climate has changed since 1950 varies considerably across forest regions (Table 1). Temperature changes have generally been greater in the west and north, with quite drastic changes occurring in the Boreal West, Montane, and Pacific forest regions. These regions have also shown strong asymmetry in their warming patterns, with MINTCM rising at a much faster rate than MAXTHM. Although DDGS is closely tied to temperature, changes in this measurement have not shown the same degree of regional variation. Degree-days are calculated as the sum of the maximum temperatures for all days over 5 ºC; thus, the drastic changes in extreme minimum temperatures observed for the three western regions have not translated into equally drastic changes in DDGS. The pattern is reversed for precipitation, with the largest increases occurring in the east; western regions have shown little change in precipitation levels or even, in the case of the Pacific region, a decline.

Table 1. Trends in 5 climate variables for 5 forest regions over the period 1950–2003 (expressed as the change in the 53-year period). The values for Canada are for all areas, not just forests.

Climate variable	Atlantic–Mixedwood	Boreal East	Boreal West	Montane	Pacific	Canada
Annual mean temperature (°C/53 yr)	0.3	0.5	2.0	1.8	1.4	1.4
Maximum temperature of the hottest month (°C/53 yr)	0.3	1.0	0.7	−0.5	0.2	0.7
Minimum temperature of the coldest month (°C/53 yr)	0.3	0.7	5.5	6.6	3.6	3.7
Annual precipitation (mm/53 yr)	75	75	23	−1	−108	30
Degree-days during growing season (heat units/53 yr)	88	121	110	106	144	118

These results are generally supported by other findings reported in the literature. Zhang et al. (2000) reported changes in temperature across Canada for the period 1950–1998: there were increases of 1–2 ºC in the west and <0.5 ºC in the east. The asymmetric warming rates presented here for minimum and maximum temperature were also identified in previous studies (e.g., Easterling et al. 1997; Vincent and Mekis 2006). As in the present study, Zhang et al. (2000) reported generally stronger precipitation trends in the east; however, they found an increase of 5%–10% in precipitation along the west coast as opposed to the 100-mm (or 5%) decline reported here for the Pacific region. The reason for this difference is unclear, but it may be related to differences in spatial scale or analytical approach between the two studies.

There are a number of sources of uncertainty in estimating climate trends. Errors inevitably arise when interpolating noisy climate station data; in this case the model errors are in the range of 1–1.5 ºC for minimum and maximum temperature and 20%–30% for precipitation (McKenney et al. 2006a). It is important to note that there are also errors in weather station data. The glass thermometers used in the past had a precision of 0.5 ºC and hence interpolation accuracy can essentially be no better. The accuracy of modern thermistors is about ±0.3 ºC. Thus, measurement accuracy can vary from station to station and over time with instrument changes. Although major data problems (e.g., decimal place errors) have been checked for and corrected, it is likely that there will always be some error associated with weather instrument readings, particularly for snow measurements, for which errors have been estimated to be as high as 50% (Goodison 1978; Sevruk 1982). Of greater concern to trend estimation are biases in the climate data that occur systematically and that vary over time, thus confounding the trend analysis. Such errors include changes in daily observation times, changes in the location of a climate station, and temperature increases resulting from increased urbanization around a station. Although the data used here have been carefully cleaned, it is likely that there are still some stations with temporal biases. However, given the large number of stations used here, the robustness of the spatial models, and the general agreement between our trends and those in the literature, we have a medium to high level of confidence in the trends presented here. Our models used all available station data (except obvious errors) to enhance the spatial coverage, whereas some of the previously cited data used cleaned or homogenized data for considerably fewer stations. A trade-off exists between spatial coverage and data fidelity.

Climate extremes are also recognized as important controls on ecosystems. There are two types of climate extremes (Easterling et al. 2000): extremes of climate statistics that occur every year, such as extremes of temperature and precipitation (including annual or monthly extremes such as a very low or very high daily temperature or a heavy daily precipitation amount), and extreme events, including drought, floods, or hurricanes, which do not necessarily occur every year at a given location. The remainder of this section discusses changes in extremes of climate statistics (the first type of climate extremes), which are easier to detect than changes in extreme events, whose spatial and temporal variability poses a challenge for trend analysis. Extreme events are considered to be those beyond the 90th percentile.

Over the last century most of southern Canada experienced trends of significant increases in daily temperature minima and maxima (Bonsal et al. 2001; Vincent and Mekis 2006). Specifically, the number of days with extreme low temperatures during winter, spring, and summer has decreased while the number of days with extreme high temperatures during winter and spring has increased (the trend in the number of hot summer days is not significant at the national scale). As noted above, this shift of extremes is asymmetrical, with the lower percentile values increasing more than the higher ones. In the same period the maximum number of consecutive dry days decreased and the number of days with heavy precipitation increased. However, no consistent change has been observed in average precipitation intensity. These national trends are also valid for the 1950–2003 period, for which a larger data set is available, particularly from northern Canada.

In a country as large and diverse as Canada, national climate trends may be quite different from those in individual regions. The analysis of

weather data from more northern locations in the second half of the 20th century has highlighted differing trend directions in, for example, extreme precipitation: for the period 1940–1995, a subgroup of 38 weather stations in northern Canada displayed a trend of pronounced increases in the fraction of annual precipitation falling in the largest 10% of events, whereas for 1910–1995 30 southern stations displayed a negative trend. Another trend emerging regionally is an upward tendency in the number of heavy spring rainfall events over eastern Canada (Zhang et al. 2001).

Detection of change is complicated by the fact that seasonal variability in the frequency and magnitude of extremes often dominates long-term trends. For example, summer heavy rainfall events were generally more common early in the 20th century and were relatively rare during the 1930s; since 1950 there has been little change in the annual number of these events. Overall, few analyses of climate extremes are available that combine regional and seasonal patterns.

2.1.2 What Are the Impacts on Forests?

A basic tenet of forest management is that climatic variables influence forest growth and stand dynamics (MacIver et al. 1989). Most directly, forest stands respond to both the average and extreme conditions that characterize a climate regime. As well, disturbance regimes, in close association with their climate controls, exert a dominant influence on forest landscape dynamics (Fleming 2000). Currently, the most obvious indication of a serious impact of climate change on forests is the greater severity of wildfires and abnormal insect infestations than in the past. Changes in forest growth, phenology, and stand dynamics are, as yet, less clear. This section summarizes current knowledge of how recent climate change has affected Canada's forests.

2.1.2.1 Fire and Biotic Disturbances

Fire is the major stand-renewing agent for much of the Canadian forest, greatly influencing forest structure and function. Currently, an average of over 2 million hectares burn annually in Canada (Stocks et al. 2002). Fire activity is strongly influenced by four factors: weather (climate), fuels, ignition agents, and human activities. Recent climate warming is likely to have had a rapid and profound impact on fire activity in boreal forests (Weber and Flannigan 1997; Soja et al. 2006). Gillett et al. (2004) used a coupled climate model (a model that simulates oceanic and atmospheric processes, their interrelations, and their effect on climate) to show that observed increases in area burned in Canada during the past four decades are the result of human-induced climate change. Additionally, it appears that temperature is the most important predictor of area burned in Canada, with higher temperatures associated with greater area burned (Flannigan et al. 2005).

The upward trend in area burned annually by wildfires in Canada since the early 1970s is undeniable, with an increase in both the number of lightning-caused fires and the average area burned per fire. Three of the four most severe fire seasons ever recorded in Canada (in terms of area burned) occurred between 1989 and 1998 (Stocks et al. 2002). More lightning-caused fires burn late in the fire season now than in the past, consistent with an extension of the duration of the fire season. The trend is generally true across the country but is more pronounced in the western boreal and taiga ecozones (Podur et al. 2002; Kasischke and Turesky 2006).

Weather (and its long-term representation as climate) is probably the most important factor influencing area burned. Through temperature, relative humidity, wind, and precipitation, weather influences fuel moisture, which determines directly if fuels will ignite and, if they do, if the fire will spread. As well, weather influences thunderstorm activity, which is the ignition agent responsible for most of the area burned in Canada (Stocks et al. 2002). Spring and summer temperatures and the number of consecutive dry days are the most direct, proximate climate drivers of forest fire activity (Flannigan and Harrington 1988; Flannigan and Van Wagner 1991). Historically, fire occurrence and area burned bore a statistically significant relation with episodes of summer drought (Girardin et al. 2006). Recent variations in monthly average temperatures during the fire season were found to explain much of the variability in area burned, consistent with a positive response of fire activity to human-induced climate change (Gillett et al. 2004).

Historical reconstructions and modeling studies indicate that the recent upward trend in fire activity reflects an early effect of a changing climate (Girardin et al. 2007). Note, however, that historically Canada may have witnessed several periods with much greater fire activity than has been seen recently. Compared with the reconstructed time series for the last 200 years, data for the second half of the 20th century display relatively low fire activity (Girardin et al. 2006). In addition to the effect of weather and climate on fire occurrence and area burned, fire-suppression extent and technology, land management practices, and ignition sources will superimpose, over long time periods, their own effects on climate-driven trends (Podur et al. 2002).

In Canada it is generally believed that the wetter eastern forests have historically been more susceptible to large-scale infestations by pests such as the spruce budworm (Fleming 2000). However, unprecedented insect outbreaks have recently occurred in western Canada, e.g., outbreaks of the mountain pine beetle in British Columbia and Alberta, the spruce bark beetle in the Yukon, and the dothistroma needle blight in northwestern British Columbia. Although these outbreaks have varied in extent, they have exceeded in scope all previous epidemics caused by each of these pest species; they have involved native species or long-term residents of the areas where the outbreaks originated; and they are associated with the crossing of a climatic threshold, in terms of either summer precipitation (Woods et al. 2005) or winter temperature (Carroll et al. 2004). The climate-driven change in the status of these pests raises much uncertainty about future insect disturbance regimes and the patterns of damage they will produce under a changing climate (Fleming 2000).

2.1.2.2 Response of Forest Stands: Growth

Few generalizations have so far emerged on the combined responses of forest growth to climate change and other human-caused changes such as increasing carbon dioxide (CO_2) concentrations in the atmosphere and increasing nitrogen deposition. Despite earlier indications that such changes should enhance forest productivity, no significant changes were detected in an analysis of forest plot remeasurement data in the eastern United States (Caspersen et al. 2000), nor have systematic changes been observed across the boreal forests (Lloyd and Bunn 2007). In Canada, the preliminary results of an ongoing national tree-ring study led by the Canadian Forest Service of Natural Resources Canada (Bouriaud et al. 2007)[1] suggest a consistent trend of increasing growth in Canada's forests before the 1940s, but since then growth trends have varied greatly by region and forest type. Thus, it is likely that local and regional growth responses to a changing climate are driven by site-specific species and stand dynamics (Hogg and Bernier 2005). For example, at both a southern and a northern site in the western boreal forest, the annual growth of black spruce (*Picea mariana* [Mill.] BSP) has responded positively to cooler and wetter conditions, whereas a positive growth response in jack pine (*Pinus banksiana* Lamb.) has been linked to increased temperature and spring precipitation (Brooks et al. 1998).

Evidence from Free Air Carbon Dioxide Enrichment experiments in the United States and Europe indicates that tree productivity and drought resistance should generally respond positively to increased atmospheric CO_2 concentrations, with an observed average increase of 23% in growth when the atmospheric concentration doubles (from pre-industrial levels to approximately 550 parts per million; the current concentration is about 385 parts per million) (Norby et al. 2005). However, our ability to extrapolate these results to determine the growth response of Canadian forest ecosystems is seriously constrained by a lack of hard evidence, as we do not fully understand how such a response may be modulated by other growth-limiting factors and physiological processes. Possible limiting factors are competitive interactions for ecosystem resources, especially nitrogen in mature stands (Reich et al. 2006), changed allocation patterns in older trees (e.g., Körner et al. 2005), and downregulation of photosynthesis (Medlyn et

[1]Bouriaud, O.; Bhatti, J.; Kurz, W.; Hogg, T. 2007. Temporal and spatial growth patterns of Canadian forests – preliminary analysis Canadian Research on Enhancement of Greenhouse Gas Sinks Final PERD POL .6.2 Workshop February 21:23–2007 Camsell Hall, Ottawa, ON.

al. 1999; Reich et al. 2006). In this context, downregulation can be defined as a drift back to former photosynthetic rates as the trees adjust biochemically to the new environment. The interaction of these growth-limiting factors with climate change may mean that some constraints will be lifted in many Canadian forests, because warmer, drier conditions are likely to promote faster mineralization of organic nitrogen presently locked up in cold wet soils, but this mechanism is still hypothetical.

Advancements in satellite-based remote sensing technologies have enabled global-scale monitoring and assessment of changes in forest productivity based on multispectral "greenness" indicators, although significant challenges remain in the large-scale validation of these indicators against ground-based measurements. Earlier reports from satellite-based monitoring showed increases in both the magnitude and duration of growing season "greenness" in the world's northern forested areas during 1981–1999 (e.g., Zhou et al. 2001). This approach has since been used in combination with modeling to infer a positive effect of warming on tundra productivity in arctic regions but relatively little change for boreal regions up to the year 2000 (Bunn et al. 2005). More recent observations, however, point to decreasing trends in the productivity of the Canadian boreal forest (Goetz et al. 2005), especially during 2001–2004, when droughts affected large areas of the boreal forest in both North America and Eurasia (Bunn et al. 2007). These results are consistent with ground-based observations from the CIPHA (climate change impacts on the productivity and health of aspens) study led by the Canadian Forest Service (Hogg et al. 2005), which recently documented the impacts of the 2001–2002 drought on aspen forests in the west-central Canadian interior (Hogg et al. 2008). These impacts included a decrease in regional-scale productivity and increased mortality of aspen, especially in the areas most severely affected by the drought.

Many portions of the Atlantic–Mixedwood region, such as the Acadian Forest region, are ecotonal in nature, being composed largely of boreal species at the southern limit of their range and temperate species at the northern limit of their range; this feature makes the region's forests particularly responsive to climate change. Evidence from the national tree-ring study (Bouriaud et al. 2007) suggests that most species in this region have been responding positively to the climate change that has occurred to date, but there are a number of indications that this trend will not continue. In recent years, several insect pests, notably the balsam woolly adelgid, *Adelges piceae* (Ratzeburg), and gypsy moth, *Lymantria dispar* (L.), have caused more damage than in the past within the Maritimes, especially in cooler areas. In addition, there have been indications of growth decline among balsam fir (*Abies balsamea* [L.] Mill.) in southern New Brunswick possibly because of drought stress.

Studies in well-defined, climate-sensitive forest landscapes have been more successful in pinning down climate-driven alterations in tree or stand dynamics and provide the best available evidence of likely responses to climate change at the local to regional level. As mentioned above, recent studies have demonstrated the vulnerability of aspen to drought in the Prairies (Hogg et al. 2005) and the unusually long delay in postfire regeneration of these mixedwood stands in the Yukon (Hogg and Wein 2005). In the Yukon, postfire regeneration and regrowth of mixedwood forests in the second half of the 20th century was much slower than expected (Hogg and Wein 2005). Tree lines also constitute a climate-sensitive environment. Spruce trees (*Picea* spp.) at the northern tree line in eastern Canada have gradually changed their growth form over the past century, going from prostrate to upright at a variety of very northern sites (Gamache and Payette 2004). In western Canada, stands of both white spruce (*Picea glauca* [Moench] Voss) and willow (*Salix* spp.) responded over the course of the last century to warmer conditions at their subarctic elevation tree line by either showing an increased density or expanding beyond their historical elevation limit (Danby and Hik 2007). Finally, the long-term decline of yellow-cedar (*Chamaecyparis nootkatensis* [D. Don] Spach) in Alaska and along the northern Pacific coast of British Columbia has been linked to climate warming (Hennon et al. 2006). Specifically, decreases in winter snow cover have caused increases in freezing injury to the shallow roots of this species, leading to large-scale forest dieback. Hence, although a climatic response is being detected in sensitive stands, the direction and magnitude of this response and the controlling factors vary.

2.1.2.3 *Response of Forest Stands: Phenology and Stand Dynamics*

In terms of phenology, climate strongly affects growth through its impact on leaf out (bud burst) and leaf fall in deciduous species, which mark the beginning and end of growing seasons, and its subtler but no less important impact on the physiology of conifer foliage. In general, dates of bud burst are far more variable than dates of leaf fall, and because sun angle is higher and solar radiation greater in the spring, early springs have a far greater impact on annual growth than late falls. Changes in species phenology and distribution offer signs of a climate-related response. Although the observed warming trend across Canada must have already influenced phenology, current observations are scattered and insufficient to support generalization, especially given the natural variability of the phenomenon. For example, using an empirical degree-day model of bud burst, Colombo (1998) estimated a trend for earlier bud burst in white spruce at only 5 of the 10 sites analyzed from across Canada, with most increases still within the range of historical variability in bud-burst dates. Because of the difficulty in detecting small changes in the context of a large degree of natural variability, our overall assessment is that it is very likely that climate change has had an effect on phenology but that the effect has yet to be widely observed and recorded.

Raulier and Bernier (2000) produced a climate-driven model of bud burst for sugar maple (*Acer saccharum* Marsh.). Their work documents the very large observed interannual variability in this phenomenon, up to 20 days for consecutive years, which may hide long-term trends. An unpublished analysis[2] using this model suggested a gradual precession of bud-burst dates, by 4–10 days over the past century. This result is consistent with the observed advance in spring bud burst ranging from 2 to 8 days for woody perennials such as lilac (*Syringa chinensis*) and ornamental grapes (*Vitis vinifera*) in northeastern United States for the period 1965–2001 (Wolfe et al. 2005). Some of the best observational work in Canada on this subject, reported by Beaubien and Freeland (2000), showed a 26-day shift in the flowering date of aspen in the Edmonton area over the past century.

2.2 What Changes in Climate Do We Anticipate in the Future?

2.2.1 Projecting Future Climate

Numerous research studies have used general circulation models (GCMs) to simulate future climate; these models include three-dimensional representations of the atmosphere, ocean, cryosphere, and land surface and parameterizations of the associated physical processes. Future climate scenarios are based on the effects of various concentrations of greenhouse gases and other pollutants within the atmosphere on the earth–atmosphere system. Transient simulations are available from GCMs that allow examination of the possible rates of change in the climate in the coming century.

For the current work, climate projections were generated for three future time periods using the output from four GCMs. These were the Canadian GCM (CGCM2; Boer et al. 2000 http://www.cccma.ec.gc.ca/models/cgcm2.shtml), the UK-based Hadley Centre Third-Generation Coupled Model (HadCM3; Gordon et al. 2000), the Australian-based Commonwealth Scientific and Industrial Research Organisation GCM (CSIRO Mk2; Gordon and O'Farrell 1997), and the US-based National Center for Atmospheric Research parallel climate model GCM (NCAR; http://www.cgd.ucar.edu/pcm/). Unless otherwise stated, the results presented here are an average of the four GCM outputs.

For each GCM we used two scenarios of future global anthropogenic greenhouse gas emissions, A2 and B2, as described in Nakicenovic and Swart (2000) and used by the IPCC in its *Fourth Assessment Report* (see Metz et al. 2007, Parry et al. 2007, and Solomon et al. 2007). Neither scenario includes new global efforts specifically designed to reduce greenhouse gas emissions. The scenarios differ in that A2 assumes much higher population growth, slower convergence of incomes across countries and regions, less forested land, greater pollution, higher energy intensity, and greater reliance on fossil fuels than does B2.

Under A2, emissions are projected to rise to close to 140 gigatonnes CO_2-equivalent per year (Gt CO_2-eq/yr) by 2100; by comparison,

[2]Unpublished analysis conducted by P.Y. Bernier, Canadian Forest Service.

emissions in 2000 were about 40 Gt CO_2-eq/yr (Metz et al. 2007). CO_2-equivalent is a measure, for a given emission of a greenhouse gas, of the amount of CO_2 that would have the same global warming potential over 100 years. Under this scenario, the IPCC's best estimate is that global average temperature would increase 3.4 °C between 1980–1999 and 2090–2099 (likely range of 2.0–5.4 °C) (Solomon et al. 2007). Under B2, emissions are projected to rise to almost 70 Gt CO_2-eq/yr by 2100 (Metz et al. 2007), with a projected temperature increase of 2.4 °C (1.4–3.8 °C) (Solomon et al. 2007). For both scenarios, warming is projected to be greatest over land and high northern latitudes — the location of Canada's forests.

The IPCC considers scenarios A2 and B2 and four others it uses to be equally sound (Nakicenovic and Swart 2000; Solomon et al. 2007). We chose these two because we felt they represent plausible low-to-medium (B2) and high (A2) global emission paths over the next century in the absence of worldwide efforts to reduce emissions. In fact, although A2 could be seen as a relatively extreme scenario, recent evidence suggests global CO_2 emissions have been increasing at rates higher than predicted in even the most pessimistic IPCC scenario (Canadell et al. 2007). Fossil fuel and cement CO_2 emissions increased during 2000–2006 at a rate of 3.3% per year, compared with 1.3% per year in the 1990s; even the A2 scenario would be conservative if this trend were to continue.

However, it is important to keep in mind that the scenarios used here do not take into account the potential for global efforts to substantially reduce emissions in the coming decades. One way to assess the impact of such efforts is to look at the IPCC B1 emission scenario. The B1 scenario describes a world in which population peaks by mid-century then declines (the world population in 2100 is lower in this scenario than in either A2 or B2), and there is a rapid change in economic structure toward a service and information economy so that energy intensity is quite low compared with that in either A2 or B2. The B1 scenario also assumes relatively rapid increases in the use of clean and resource-efficient technologies and a relatively high reliance on nonfossil energy sources, although not as a result of new measures specifically aimed at addressing climate change (Nakicenovic and Swart 2000; Solomon et al. 2007). Under this scenario, greenhouse gas emissions in 2100 would be about 25 Gt CO_2-eq/yr or about 40% lower than in 2000 (Metz et al. 2007). Even so, in scenario B1 global temperature is still predicted to rise by the end of the century to 1.8 °C above the average for 1980–1999 (likely range of 1.1–2.9 °C) (Solomon et al. 2007). Increases in temperature could be higher in much of Canada's forested area. The IPCC (Parry et al. 2007) suggests that an increase of this magnitude, although smaller than the increases examined in detail here, is still capable of bringing about considerable change in the global ecosystem, including increased risk of species extinction, increased movement and migration of species, and increased frequency and intensity of wildfires. Thus, forest sector adaptation will still be important.

2.2.2 Projections of Future Climate in Canada's Forests

To generate the future climate grids, average change surfaces were generated for each time period (2011–2040, 2041–2070, 2071–2100) by interpolating the changes predicted by each GCM and emission scenario (McKenney et al. 2006b). These change estimates were then added to 1971–2000 climate station normals, and these adjusted station values were used to generate the final climate grids. Thus, the results represent Canadian and American climatology as provided by the existing network of climate stations in combination with the broad-scale average changes predicted by the climate change scenarios. As in section 2.1.1 and Table 1, the focus is on AMT, MAXTHM, MINTCM, ANNP, and DDGS. We also examine moisture using the Climate Moisture Index, described below. Here we look only at projected changes to 2100, but climate would continue to change well beyond that date.

Projected changes in AMT and MAXTHM are relatively consistent across regions, with temperatures increasing by 1–2 °C in the short term and 4–5 °C by the end of the century (Table 2). Changes are somewhat more variable for MINTCM, ranging from a projected increase of nearly 8 °C for the Boreal East region to an

increase of only 3 ºC for the Pacific region by the end of this century. For all temperature variables, predicted changes were 1–2 ºC less for the B2 scenario than for the A2 scenario, reflecting the lower emissions associated with the former scenario. Under the A2 scenario, the Atlantic–Mixedwood region is predicted to experience an increase of nearly 1000 degree-days by the end of the century; all other regions are expected to experience an increase of 500–700 degree-days over this period. For all regions, under the B2 scenario the predicted increases are lower by about 200 degree-days than under the A2 scenario.

An example of spatial and temporal detail is provided for projected changes in annual mean temperature in Figure 2. This time series of maps shows how annual mean temperature is predicted to change in the near future (2011–2040), medium term (2041–2070), and long term (2071–2100) on the basis of projections from the Canadian GCM under the A2 emission scenario. According to these projections, increases of 3–5 °C would be common across the forested regions of Canada. The use of another GCM or emission scenario would yield different projected changes and spatial and temporal variations. However, as in Figure 2, different projections all tend to show that the greatest changes are predicted for northern Canada and the Prairies.

Annual precipitation is predicted to increase in all regions over the course of the century under the A2 scenario; the increase ranges from 6% in the Atlantic–Mixedwood region to 17% in the Boreal West region. The B2 scenario predicts precipitation changes that are only 1–2 percentage points lower than those predicted by the A2 scenario. It is important to note, however, that increases in precipitation do not necessarily translate into moister conditions, because higher temperatures lead to greater rates of evaporation and transpiration (collectively referred to as evapotranspiration). For example, the treeless, semiarid areas of southern Alberta currently receive more precipitation (350–400 mm) than the forested areas around Yellowknife, Inuvik, and Whitehorse (260–300 mm per year). Despite their low annual precipitation, these northern locations are much moister (and support forests) because their cold climates and short growing seasons result in lower rates of evapotranspiration. Thus, the balance between water input (precipitation) and water loss to the atmosphere (evapotranspiration) needs to be considered when assessing the impacts of climate change on moisture regimes and forest responses.

The Climate Moisture Index developed by Hogg (1994, 1997) provides a useful method for assessing differences in moisture regimes both spatially and temporally, using simple climate data (temperature and precipitation). The Climate Moisture Index is calculated as the difference between annual precipitation and potential evapotranspiration and is expressed in units of centimetres water balance per year. Positive values denote moist conditions that typically support closed-canopy forests, whereas negative values denote dry conditions typical of prairies or patchy, open-canopy forests (e.g., parkland). Figure 3 shows moisture conditions based on the Climate Moisture Index for the recent historic period (1961–1990) and for the future as predicted by CGCM2 using the A2 emissions scenario. The maps show that despite the projected increases in precipitation, prairie-like climates (negative Climate Moisture Index) are expected to expand northward to encompass large areas of the western boreal forest. With the exception of the Pacific region, Climate Moisture Index values are expected to decline in all regions, with more rapid climatic drying under the A2 scenario (Table 2), although the effects are likely to be less noticeable in regions that already have abundant moisture.

Although not shown here, the predictions of future climate made by the different GCMs vary considerably. The CSIRO GCM consistently predicts steeper trends than all other GCMs for both temperature and precipitation variables. Of the remaining GCMs, CGCM2 and HadCM3 are relatively similar in their estimates, whereas NCAR consistently predicts the least change over the next century.

Several sources contribute to uncertainty in the climate projections. The main ones are related to the GCM outputs as driven by certain climate drivers such as the role of clouds and their radiative effects, modeling the hydrological balance over land surfaces, and capturing the heat flux at the ocean surface. In the IPCC *Fourth*

Table 2. Estimates of recent and projections of future climate variables in Canada's forest regions. Projections are derived from the averages of 4 global climate model outputs for IPCC future global greenhouse gas emission secenarios A2 and B2[a]. The values for Canada are based on the whole country, not just forested regions.

Period	Atlantic–Mixedwood		Boreal East		Boreal West		Montane		Pacific		Canada	
	A2	B2	A2	B2	A2	B2	A2	B2	A2	B2	A2	B2
Annual mean temperature (°C)												
1961–1990	4.9	4.9	−1.6	−1.6	−4.6	−4.6	1.2	1.2	3.8	3.8	−2.4	−2.4
2011–2040	6.2	6.5	−0.1	0.1	−3.2	−2.9	2.2	2.6	4.7	5.1	−1.0	−0.7
2041–2070	7.6	7.3	1.4	1.1	−1.8	−2.1	3.5	3.3	5.9	5.7	0.5	0.1
2071–2100	9.6	8.4	3.7	2.2	0.3	−1.0	5.3	4.3	7.5	6.6	2.6	1.3
Maximum temperature of the hottest month (°C)												
1961–1990	24.7	24.7	20.6	20.6	20.5	20.5	19.5	19.5	17.7	17.7	20.8	20.8
2011–2040	26.1	26.3	21.9	22.2	21.4	21.8	20.9	21.3	18.9	19.3	22.0	22.3
2041–2070	27.3	27.2	23.3	23.2	22.9	22.4	22.5	22.3	20.4	20.0	23.5	23.2
2071–2100	29.4	28.1	25.4	24.1	24.6	23.4	24.5	23.2	21.8	20.8	25.4	24.1
Minimum temperature of the coldest month (°C)												
1961–1990	−15.1	−15.1	−25.7	−25.7	−29.8	−29.8	−15.1	−15.1	−7.0	−7.0	−26.1	−26.1
2011–2040	−13.8	−13.3	−23.7	−23.1	−28.7	−28.1	−14.7	−13.3	−6.9	−5.7	−24.8	−24.1
2041–2070	−11.3	−12.0	−20.8	−21.6	−26.3	−27.6	−12.7	−14.4	−5.3	−6.7	−22.2	−23.4
2071–2100	−9.2	−10.3	−17.9	−19.6	−23.3	−25.3	−10.7	−11.4	−3.5	−4.3	−19.4	−21.1
Degree-days during growing season[b]												
1961–1990	1502	1502	792	792	725	725	638	638	752	752	807	807
2011–2040	1770	1826	991	1034	889	920	802	834	916	957	992	1029
2041–2070	2030	1989	1198	1156	1077	1038	1004	985	1136	1101	1195	1157
2071–2100	2476	2192	1553	1319	1346	1167	1300	1116	1444	1251	1511	1302

Table 2. Concluded.

Period	Atlantic–Mixedwood		Boreal East		Boreal West		Montane		Pacific		Canada	
	A2	B2	A2	B2	A2	B2	A2	B2	A2	B2	A2	B2
Annual precipitation (mm)												
1961–1990	1107	1107	842	842	407	407	726	726	1799	1799	616	616
2011–2040	1132	1134	878	880	430	431	746	752	1795	1826	642	644
2041–2070	1170	1160	901	901	448	447	769	757	1830	1809	662	660
2071–2100	1171	1166	935	918	476	464	789	780	1906	1864	690	677
Climate Moisture Index[c] (cm)												
1961–1990	66.5	66.5	55.8	55.8	13.1	13.1	37.4	37.4	145.0	145.0	31.3	31.3
2011–2040	64.2	63.3	55.8	55.1	12.7	12.1	35.4	35.4	145.0	147.4	30.9	30.1
2041–2070	63.2	62.8	54.1	54.7	10.9	11.7	32.5	31.7	144.0	142.7	28.8	29.2
2071–2100	54.5	59.3	50.8	53.4	8.2	11.0	27.1	31.0	146.1	145.4	25.3	28.2

[a] Emission scenarios: A2 = scenario with a regionalized global economy in which the rate of increase in greenhouse gas emissions is comparable to the rate of increase in the 1990s. B2 = scenario with a regionalized global economy in which societies are more socially and environmentally conscious than in scenario A2, with slower population growth, lower energy intensity, and less reliance on fossil fuels, leading to a much lower rate of growth in greenhouse gas emissions.
[b] An indicator of total heat available for plants in the growing season.
[c] A measure of moisture available to plants throughout the year. A reduction indicates less moisture available.

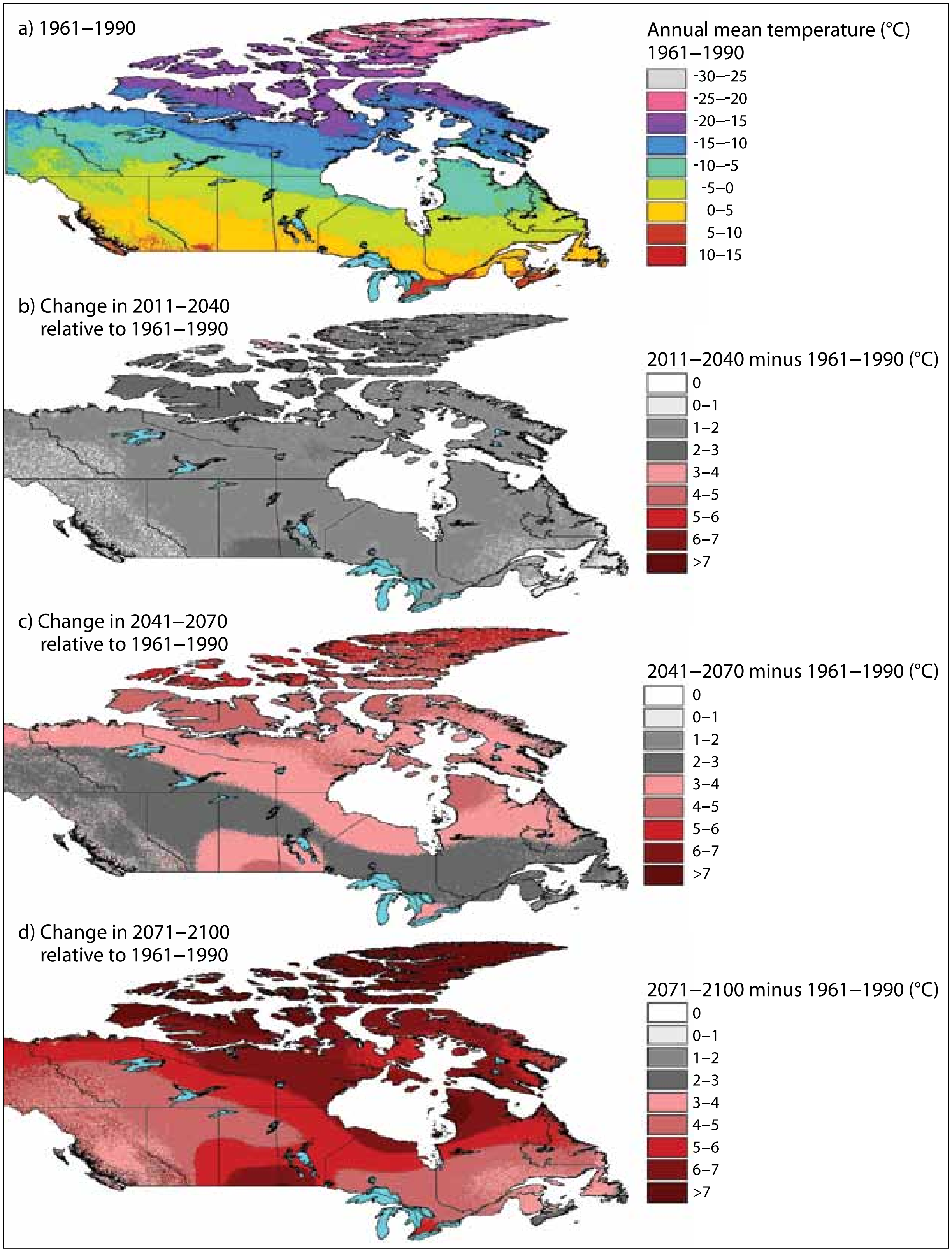

Figure 2. An example of spatial and temporal variation in projected future changes (CGCM2–A2) in annual mean temperature for Canda. a) Recent (1961–1990) annual mean temperature and change relative to 1961–1990 for b) 2011–2040, c) 2041–2070, and d) 2071–2100. CGCM2–A2 = Canadian Second-Generation Coupled Global Climate Model.

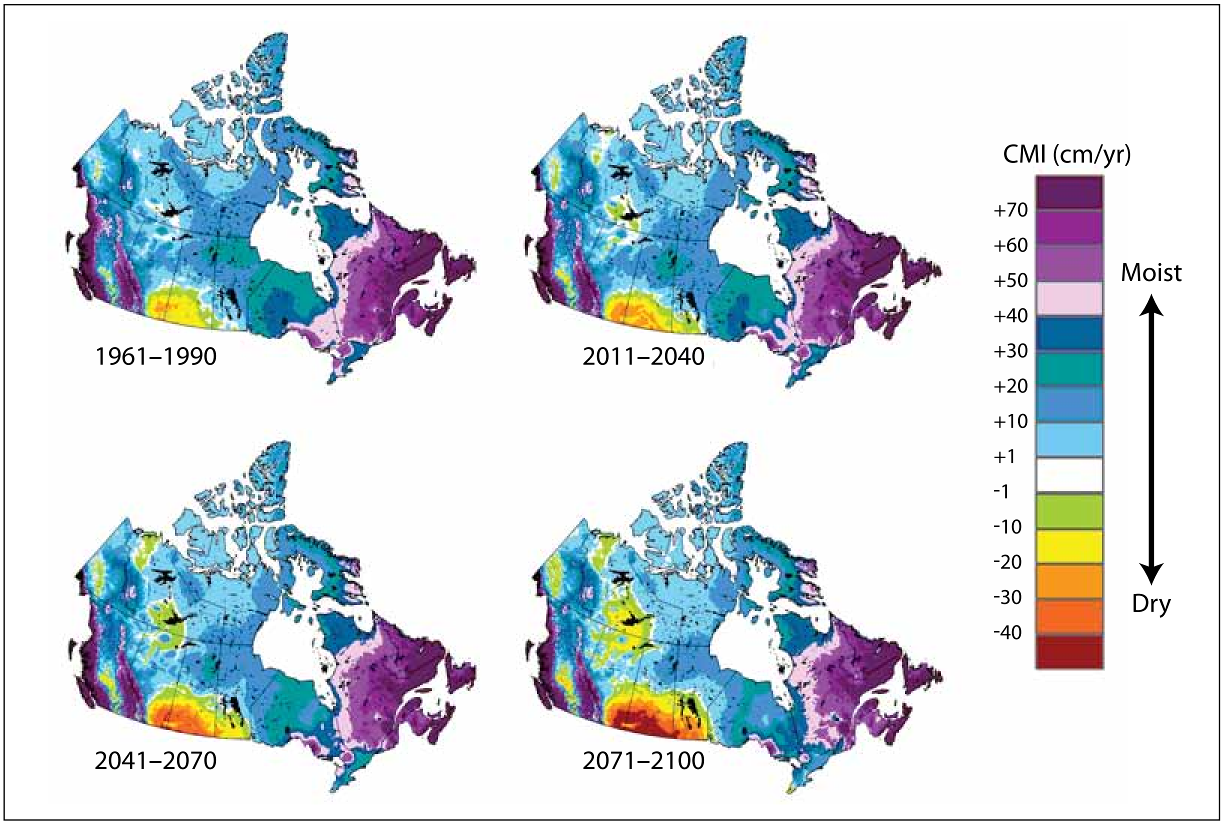

Figure 3. Historical and projected future (CGCM2–A2) moisture regimes based on the Climate Moisture Index (simplified Penman-Monteith method of Hogg [1997]). Negative values denote dry conditions typical of prairie or parkland climates. CMI = Climate Moisture Index, CGCM2–A2 = Canadian Second-Generation Coupled Global Climate Model with the A2 scenario in which the rate of increase in greenhouse gas emissions is comparable to the rate of increase in the 1990s. Maps by D. Price, M. Siltanen, and D. McKenney.

Assessment Report (Solomon et al. 2007), GCM predictions of future temperatures are shown with a ±2 °C likely range around mean values. The IPCC rates the certainty of its century-end temperature and precipitation projections derived from an ensemble of GCMs as very likely. Because we are using many of the same data for the current work, we follow the IPCC in suggesting that the projections provided above are very likely to happen, at least in a general sense, if either emissions scenario is realized.

2.3 What Are the Expected Future Impacts on Canada's Forests?

In this section we summarize available information about how changes in climate such as those described earlier will affect the forest until the end of the 21st century. As before, we examine fire, insect, and other biotic disturbances, and forest growth and succession.

As previously noted (at the beginning of section 2.2), these factors will interact in complex nonlinear ways; therefore, to be considered complete, an assessment must acknowledge these interactions even if they are not yet fully understood or documented. In addition, these factors would continue to have an impact beyond 2100 because the climate would continue to change.

2.3.1 Disturbances: Fire

Table 3 displays a summary assessment of the current trend in area burned for five forested regions as well as what we anticipate for the near term (2011–2040), medium term (2041–2070), and long term (2071–2100). The basis for this assessment is discussed in this section.

Currently, almost all of the forest area burned is located in the Boreal East and Boreal

Table 3. Qualitative assessment of changes in the size of area affected by fire as a result of climate change, by forest region

Period	Atlantic–Mixedwood	Boreal East	Boreal West	Montane	Pacific	Canada
Now	NC	++	+++	--	--	++
Near-term (2011–2040)	NC	++	+++	++	+	++
Medium-term (2041–2070)	+	+++	+++	+++	++	+++
Long-term (2071–2100)	++	+++	+++	+++	+++	+++

NC = no change observed/expected. Scale of change in area burned is indicated as follows.
Increase: + low, ++ moderate, +++ high. Decrease: - low, -- moderate, --- high.

West regions (23% and 75% of the area burned, respectively, in 1959–1999). Significant increases in area burned in these regions are expected in the future. Less than 2% of the area burned is located in the other three regions. The Atlantic–Mixedwood region has extensive agricultural and urban areas, resulting in reduced forest cover and fragmentation of the landscape, which in turn reduces the amount of fire. In the Montane and Pacific regions, fire activity has been relatively low, largely because of fire-suppression activities. For all three of these regions, especially the Montane region, the fire weather severity is expected to increase in the future and lead to an increase in fire activity. Also, fire activity in the autumn may become more prominent with the lengthening of the fire season in the Atlantic–Mixedwood region.

Many studies have addressed the impact of climate change on fire weather severity. Flannigan and Van Wagner (1991) compared the values of the seasonal fire severity rating index (a measure of the difficulty of fire control, which is a component of the Canadian Forest Fire Weather Index System) in a 1 × CO_2 scenario and a 2 × CO_2 scenario across Canada. The former scenario represented the current CO_2 levels at the time of the study while the latter was a scenario in which the greenhouse gas contribution to the atmosphere would be equivalent to that from a doubling of CO_2, which was expected to occur at approximately the middle of the 21st century. They used monthly anomalies of temperature and precipitation from three GCMs. The results suggest increases in the seasonal severity rating across Canada, with an average increase of nearly 50%, translating roughly into a 50% increase in area burned. Stocks et al. (1998) used monthly data from four GCMs to examine climate change and forest fire potential in Russian and Canadian boreal forests. Forecasted seasonal fire weather severity was similar for the four GCMs, indicating large increases in the spatial extent of extreme fire danger in both countries under a 2 × CO_2 scenario.

Stocks et al. (1998) also conducted a month-to-month analysis, which showed an earlier start to the fire season and significant increases in the area experiencing high to extreme fire danger in both Canada and Russia, particularly during June and July. Flannigan et al. (1998) used daily output from the Canadian GCM to model potential fire danger with the Canadian Fire Weather Index (a dimensionless relative numerical rating of fire intensity used as a general index of fire danger) for both the 1 × CO_2 and 2 × CO_2 scenarios for North America and Europe. Most studies show large regional variation in the response of fire weather severity to climate change, with some regions showing significant increases and other regions showing no change or decreases in fire weather severity (e.g., Bergeron and Flannigan 1995; Flannigan et al. 2000). The consequences of climate change for fire disturbance must be viewed in a spatially dependent context. Only a few studies have quantified the potential changes in area burned as a result of climate change. Flannigan et al. (2005) used historical relations between weather and fire danger and area burned in tandem with two GCMs to estimate future area burned in Canada (Fig. 4). The results suggest a 74%–118% increase in area burned by the end of this century for a 3 × CO_2 scenario.

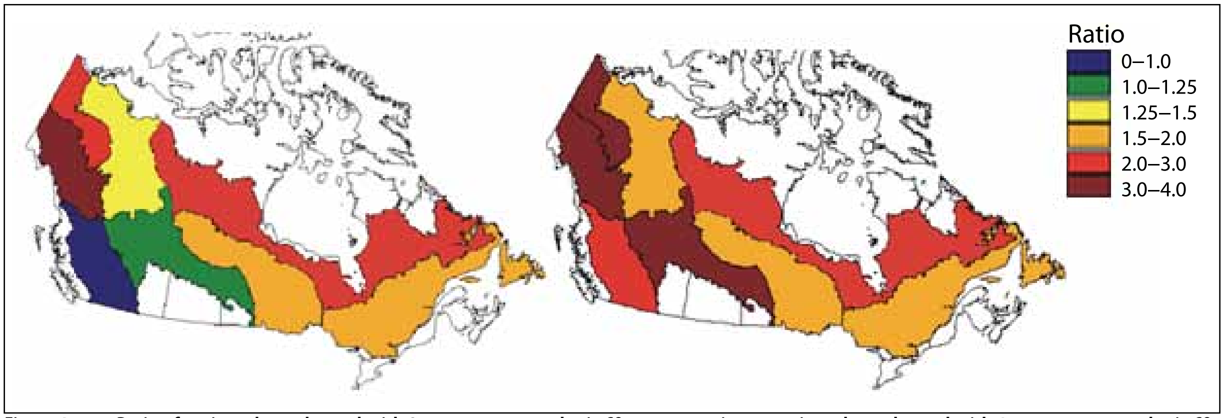

Figure 4. Ratio of projected area burned with 3× current atmospheric CO_2 concentration to projected area burned with 1× current atmospheric CO_2 concentration by ecozone using the Canadian and Hadley general circulation models, respectively. The area burned model did not work for one ecozone for the Canadian general circulation model.

Bergeron et al. (2004) discussed implications of a changing fire regime on sustainable forest management in Canada. They found that future fire activity in this century is predicted to be lower than the fire activity in the preindustrial era for many sites across the boreal forest and suggested that forest management could potentially be used to recreate the forest age structure of fire-dominated preindustrial landscapes. It is likely that other factors such as ignition agents, length of the fire season, and fire management policies will greatly influence the impact of climate change on fire activity. Ignition probabilities may increase in a warming world owing to increased cloud-to-ground lightning discharges (Price and Rind 1994), although changes in vegetation must also be accounted for, as these may greatly influence the lightning ignitions and area burned.

Projected changes in fire weather owing to climate change have been used to examine resultant changes in fuel moisture and consequently changes in fire occurrence rates in parts of the Canadian boreal forest. Both human- and lightning-caused fires are strongly influenced by moisture in the fuels of the forest floor (Wotton 2008), although these two types of fire ignite through different processes and should be considered separately in analyses of future potential for fire occurrence. Apart from the obvious need for human activity to provide an ignition source, human-caused fire occurrence is most strongly influenced by the receptivity of surface litter to ignition. Wotton et al. (2003) carried out a detailed study of future human-caused fire occurrence in Ontario using daily projections of fire weather and fuel moisture from two GCMs (CGCM2 and HADCM2). Their data showed that although changes in human-caused fire occurrence will vary spatially across the province, overall an 18% increase is expected by the year 2020 and a 50% increase by the end of the 21st century.

Although human-caused fires constitute just over 50% of fires occurring in Canada, lightning-caused fires tend to be the major contributor to area burned in the boreal forest of Canada (Stocks et al. 2002). Lightning fire ignition is strongly influenced by the moisture content in the organic layers of the forest floor. Wotton et al. (2005) examined the occurrence of lightning fires using fire weather and fuel moisture scenarios derived from the CGCM2 and found a projected increase in lightning fire activity of 24% by 2040 and 80% by the end of the 21st century. They used the relatively conservative approach of employing monthly anomalies to generate fire weather scenarios (following the method of Stocks et al. 1998), not accounting for a lengthening fire season and not including changes in lightning activity; thus, they hypothesized that their projected increases in fire activity were quite conservative.

The exposure of large areas of previously frozen and wet peatlands to fire is expected to increase significantly as a result of climate change. The feedback of carbon losses from peatland

fires has the potential to be a major factor in our changing climate. There is the possibility of positive feedback, whereby a warmer and drier climate will create conditions conducive to fire. This in turn will increase emissions of CO_2 and other greenhouse gases from fires, which will feed the warming. There is also a growing concern that peatland fires will burn more deeply in exposed organic material, making fire suppression much more difficult. Much more time and effort would be required to extinguish such fires, occupying resources that might otherwise be used to attack new fires. In addition, there is the very real possibility that holdover fires (fires that continue to smolder under snow cover during the winter and reappear the following spring) could become much more common as the number of peatland fires increases.

Climate warming is expected to lengthen the fire season. Wotton and Flannigan (1993) estimated that the length of the fire season in Canada will increase on average by 22% or 30 days in a 2 × CO_2 world (approximately mid 21st century). Also, research has suggested that the persistence of blocking ridges in the upper atmosphere will increase in a 2 × CO_2 climate (Lupo et al. 1997), which could have a significant impact on forest fires because these upper ridges are associated with dry and warm conditions at the surface and are conducive to the development of large forest fires (Skinner et al. 1999, 2001).

Fire management policies and their effectiveness will continue to change. Changes in prevention programs, initial attack capabilities, and policies of restricted access and fire restriction will influence fire activity in this century. These confounding factors may dampen or amplify the impact of a changing climate on the fire regime. Recent work now under review suggests that previous analyses may be conservative and that fire activity in Canada and Alaska may show increases of 3.5 to 6 times recent levels by the end of this century.

2.3.2 Disturbances: Biotic

Herbivorous insects, pathogens, and parasites are integral components of forests. They affect the structure and function of forest ecosystems and all of the values we derive from these ecosystems. In any forest type a diverse assemblage of species feeds upon trees. The vast majority of these species are benign or even beneficial to the growth and development of forests. However, a relatively small number of species are capable of spreading over extensive landscapes and causing acute growth loss or mortality for a very large number of trees (for a comprehensive list of North American species, see Ayres and Lombardero 2000). These species are considered biotic disturbance agents. In any given year, the area of forests in North America affected by biotic disturbance agents and the costs related to these disturbances are often many times greater than those associated with wildfire (e.g., Dale et al. 2001). Furthermore, the presence of dead trees resulting from biotic disturbance can affect the occurrence and severity of subsequent wildfires (e.g., Bergeron and Leduc 1998; Fleming et al. 2002), thereby amplifying the impacts of these diverse disturbances.

Individual species of herbivorous insects, pathogens, and parasites are highly specific in terms of the types of tissue they consume (i.e., roots, stems [phloem, sapwood, heartwood], and foliage). Generally, damage to foliage and roots impairs tree growth (although repeated impacts may kill trees), whereas damage to the stem often causes direct mortality (e.g., Johnson and Lyon 1988). Furthermore, biotic disturbance agents tend to be specific to a particular tree species or genus at a particular age (i.e., young, mature, or overmature) and in a particular environment. Because these conditions vary spatially and temporally within forests, the suite of biotic agents that affect trees and their ultimate impacts (growth loss versus mortality) will vary significantly at any given location and at any given time.

Table 4 displays a summary assessment of the current trend in the scale of impact of climate change on biotic disturbances for five forested regions as well as what we anticipate for the near term (2011–2040), medium term (2041–2070), and long term (2071–2100). The basis for this assessment is discussed in this section.

The relation between climate and the abundance and distribution of biological disturbance agents is complex (reviewed by Ayres and Lombardero 2000). Temperature

Table 4. Qualitative assessment of the scale of impact of climate change on biotic disturbance, by forest region. The assessment considers size of area affected, severity and frequency.

Period	Atlantic–Mixedwood	Boreal East	Boreal West	Montane	Pacific	Canada
Now	NC	NC	++	+++	+	+
Near-term (2011–2040)	+	+	+++	++	++	++
Medium-term (2041–2070)	++	++	+++	?	++	+++
Long-term (2071–2100)	?	?	?	?	?	?

NC = no change observed/expected. ? = uncertain. Scale of change in area affected by biotic disturbance is indicated as follows. Increase: + low, ++ moderate, +++ high. Decrease: - low, -- moderate, --- high.
Note: the anticipated decline in area affected, and the early transition to "unknown" in the Montane region in the near and medium terms, respectively, is a result of the unprecedented impact and imminent collapse of the current mountain pine beetle epidemic.

and precipitation directly influence the survival, reproduction, dispersal, and distribution of insects, pathogens, and parasites. At the same time, temperature and precipitation (and solar radiation and atmospheric CO_2) indirectly affect tree physiology and physiognomy in ways that influence responses to infestation and infection. These direct and indirect climate impacts will also affect the competitors and natural enemies that restrict biological disturbance agents. Furthermore, direct and indirect climate effects may interact with anthropogenic influences on forests such as fragmentation, pollution, fire suppression, and introduction of alien species. Thus, it is very challenging to quantify the role of climate on the dynamics of individual biotic disturbance agents. When one also considers the inherent spatial and temporal variability in the occurrence of biotic disturbance agents, it is clear that predicting the effects of climate change on these agents is extremely difficult.

In the absence of predictions of the effects of climate change on specific biotic disturbance agents, some broad generalities regarding the frequency and severity of biotic disturbance in the future can be postulated on the basis of circumstantial evidence. In an investigation of the association between historic climate warming events and insect herbivory, Wilf and Labandeira (1999) found that during the late Palaeocene – early Eocene global warming interval (about 55 million years ago), the severity of herbivory at a given location increased significantly. Although the rate of warming then was much slower than that anticipated in the near future (i.e., warming occurred over millennia versus decades), it is very likely that, given the high mobility, fecundity, and short generation time of insects (reviewed by Logan et al. 2003), a significant increase in insect herbivory in Canadian forests will accompany climate change.

Assuming such an increase in biotic disturbance as a consequence of climate change, additional generalizations can be made with respect to the type of response that broad groups of biotic disturbance agents will exhibit. Potential biotic disturbance agents may exhibit landscape-level responses to climate change in one the following four categories, depending on their spatial and temporal ubiquity. For species that can be found throughout their host-tree distribution (i.e., native ubiquitous species), a warming environment has the potential to affect the frequency, duration, and severity of disturbance events. For species that are native but do not occupy the entire distribution of their host trees (i.e., native invasive species), climate change will potentially affect the range over which disturbances will occur, as well as the frequency, duration, and severity of disturbance events. For species that are native but have historically not caused notable impacts (i.e., native innocuous species), changing climate has the potential to alter population dynamics and allow widespread disturbance. Finally, for introduced species (i.e., alien invasive species), a warming environment may increase the probability that the species will establish itself, persist, and have a greater impact in the future. It should be stressed that these generalizations do not preclude other possible impacts of climate change on biotic disturbance agents in each of the categories. For

example, Fleming (2000) proposed that climate change may facilitate host switching by some herbivorous insects, which in turn may result in (additional) range expansion by organisms.

Despite the challenges associated with trying to predict future impacts of individual biotic disturbance agents under climate change, projections have been developed for two major species in Canada. The spruce budworm (a native ubiquitous species) is arguably the most significant biotic disturbance agent in central and eastern Canada. Population densities of this defoliator have exhibited reasonably regular 30- to 40-year cycles for at least the past three centuries (Royama 1992). Recently, Gray (2008) and Candau and Fleming (2005) developed statistical models of outbreak characteristics in relation to climate, forest, and spatial variables. Gray (2008) projected future outbreak characteristics to the period 2081–2100 on the basis of simulations derived from the CGCM3 model and the IPCC B1 global greenhouse gas emission scenario (a scenario that projects lower future emissions than the B2 scenario referred to earlier in this report). On average, Gray predicted that future outbreaks would last 6 years longer and produce 15% more defoliation (Fig. 5). Interestingly, in spite of the widespread increase in the average duration of outbreaks, Gray (2008) predicted that the increase in outbreak severity would occur primarily at the southern and northern margins of the spruce budworm's outbreak distribution, with a concomitant decline in severity in the central portion of its range. This is in keeping with speculation by Volney and Fleming (2000) that higher frequencies of spruce budworm outbreaks at the southern margins of its range may occur with temperature-induced drought stress to host trees, and that an improvement in springtime synchrony between initiation of larval feeding and bud burst could extend the range of outbreaks toward the north.

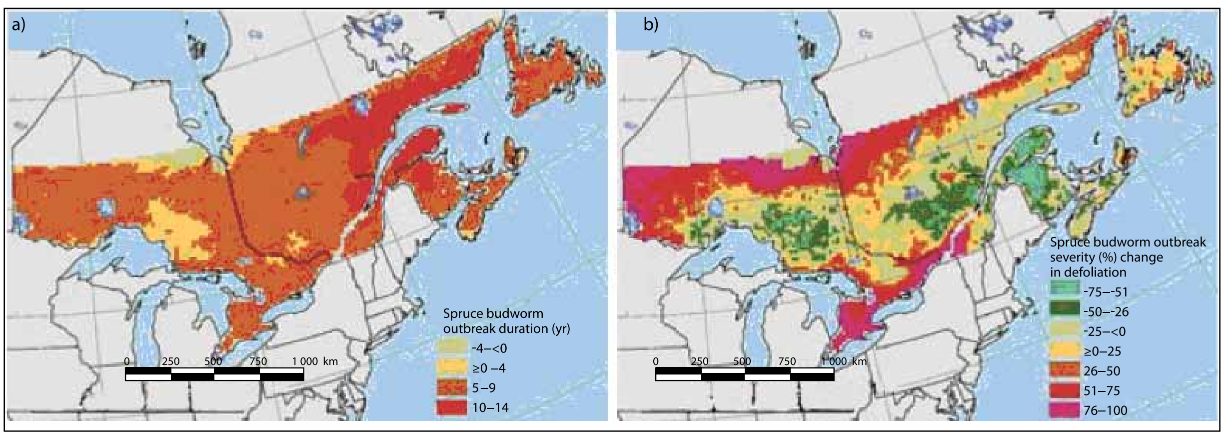

Figure 5. Projected changes (2081–2100 values minus historic values) in (a) spruce budworm outbreak duration (years), and (b) severity (percent change in area defoliated). Adapted from Gray (2008) with permission of Springer Science and Business Media.

The mountain pine beetle (a native invasive species) is the most significant pest of pine forests in western North America. Carroll et al. (2004, 2007) adapted an empirical model of outbreak probability (Safranyik et al. 1975) to determine the past, present, and future distribution of climatically suitable habitats. By comparing the annual occurrence of infestations with maps of the historic distribution of climatically suitable habitats they found that, owing to a warming environment in recent decades, mountain pine beetle populations have rapidly expanded into formerly climatically unsuitable habitats, especially toward higher elevations and more northerly latitudes. This expansion in range includes the recent invasion of the pine forests along the northeastern slopes of the Rocky Mountains immediately adjacent to the boreal forest. To determine the future distribution of climatically suitable habitats across Canada's boreal forest, Carroll et al. (2007) applied the climatic suitability model along with projections of future climate derived from the CGCM1 (Flato et al. 2000) and a greenhouse gas emission scenario equivalent to the B2 emissions scenario (Solomon et al. 2007). Their results indicate that the climate of the boreal pine forests will become increasingly suitable for the mountain pine beetle in the near future (Fig. 6). Thus, invasion of the boreal forest by this pest appears likely, although the effect of this range expansion would likely be less severe than that observed recently in British Columbia, and the potential negative impacts of other forms of change (i.e., forest fragmentation, introductions of invasive species, increased wildfire) have not yet been considered.

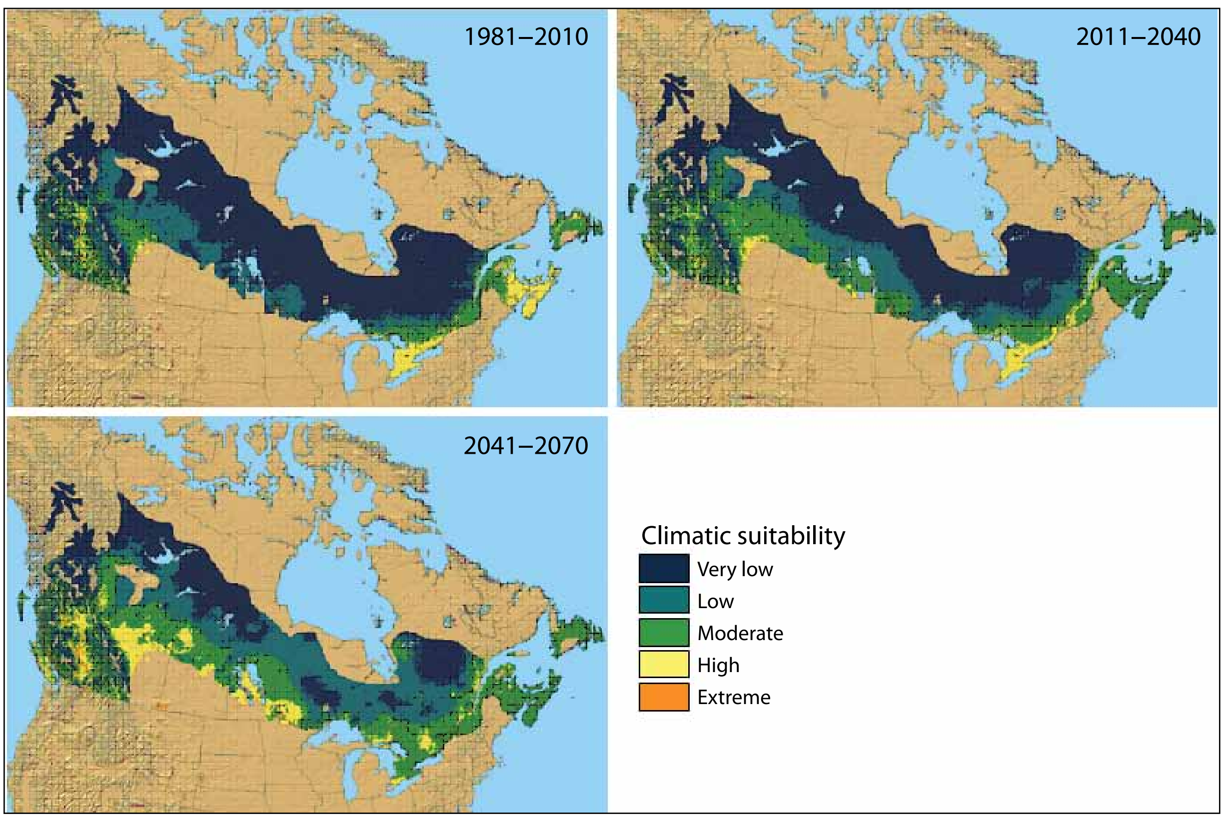

Figure 6. Future distributions of climatically suitable habitats for the mountain pine beetle in Canada's pine forests (lodgepole, jack, eastern white and red pines) derived from a climatic suitability model and the CGCM1 with an emission scenario equivalent to a 1% per year increase in atmospheric CO_2. Areas with "very low" and "low" suitability are unsuitable for mountain pine beetle whereas "high" and "extreme" areas are those considered climatically optimal. Adapted from Carroll et al. (2007) with permission of Pacific Forestry Centre.

Uncertainty regarding forecasts of the impacts of biotic disturbance in Canadian forests under climate change is highly nonlinear. Indeed, in the near to medium term (i.e., up to 2070), uncertainty may actually decrease (Table 4). This is due to the tendency for tree species that have established on a site to persist there long after the conditions that led to their establishment have disappeared (Payette 1993). As a result, in the face of a rapidly changing climate, the current structure of Canadian forests (in terms of distribution and species composition) will change relatively slowly, and therefore forests will be prone to widespread climate-induced stress. It is widely considered that tree stress arising from unusual weather patterns, such as those anticipated with climate change, may be the primary factor underlying broad-scale biotic disturbances in forest ecosystems throughout the world (White 1984; Mattson and Haack 1987; Larsson 1989; Ayres and Lombardero 2000). Thus, as long as existing forests are subject to increasing stress as a result of global climate change, it is very likely that they will experience elevated levels of biotic disturbance. However, as the area and intensity of impacts increase, the probability of sudden and catastrophic shifts in ecological state owing to disturbance may also increase (Fleming 1996), leading to a very rapid increase in uncertainty concerning subsequent disturbance forecasts.

The degree of certainty with which we can predict short-term increases in biotic disturbance in response to climate change may also vary depending upon the type of disturbance agent being considered. Although there is considerable evidence that climate-induced changes in plant physiology can affect insect herbivores, analogous studies involving pathogens are few and their results are equivocal (reviewed by Ayres and Lombardero 2000). In many instances, the dynamics of plant pathology rely to a large extent on genetic regulation of host–pathogen interactions rather than environmental effects (e.g., Glazebrook et al. 1997). For example, climatic effects on tree physiology are relatively inconsequential when compared with the importance of tree genetics for the aggressive pathogens that cause Dutch elm disease (*Ophiostoma novo-ulmi* Brasier) and chestnut blight (*Cryphonectria parasitica* (Murrill) Barr) (Ayres and Lombardero 2000). By contrast, for other major pathogen disturbance agents, such as those causing armillaria root rot (*Armillaria* spp.), annosum root rot (*Heterobasidion annosum*), and black stain root diseases (*Leptographium* spp.), the effects of climate change on tree physiology are expected to be important (reviewed by Ayres and Lombardero 2000).

Given the tendency of our existing forests to persist in areas that become increasingly unsuitable under climate change, the suite of biotic disturbance agents in the short term will largely comprise those with which we have some familiarity. It is reasonable to speculate about the future impacts of some of the major biotic disturbance agents in Canada on the basis of what we know about the role of weather and climate in their ecology and population dynamics.

The forest tent caterpillar and the jack pine budworm (*Choristoneura pinus pinus* Freeman) (both native ubiquitous species) are defoliating insects that cause significant damage to Canada's forests. For these species, Volney and Fleming (2000) predicted an increase in the occurrence of outbreaks along the southern margins of their ranges because of drought resulting from climate change. They also predicted a northward expansion in the distribution of outbreaks owing to a decreased likelihood of catastrophic loss of suitable foliage as a consequence of late spring frosts.

The gypsy moth, an alien invasive species, has spread to occupy much of the temperate hardwood forested area of northeastern North America since its introduction near Boston, Massachusetts, during the late 1800s. Gray (2004) estimated an increase of 95 million hectares (16%) in the potential range of the gypsy moth in Canada with a 1.5 °C increase in mean daily temperature.

The spruce beetle, a native ubiquitous bark beetle, has periodically killed large areas of mature spruce forests across Canada. Evidence indicates that the recent unprecedented outbreaks in northwestern North America have been exacerbated by climate change through direct impacts on beetle voltinism (i.e., a shift from a 2-year to a 1-year life cycle) and indirect impacts via temperature-induced drought stress

of host trees (Berg et al. 2006). It is very likely that, under climate change, future spruce beetle impacts will increase throughout the range of its host trees for the same reasons.

We know relatively little about the effect of weather and climate on the dynamics of several other major biotic disturbance agents in Canadian forests, including several defoliators (western spruce budworm, *Choristoneura occidentalis* Freeman; hemlock looper, *Lambdina f. fiscellaria* (Gn.); Douglas-fir tussock moth, *Orgyia pseudotsugata* (McDunnough); black-headed budworm, *Acleris gloveranus* (Walsingham) and *A. variana* Fernald), bark beetles (Douglas-fir beetle, *Dendroctonus pseudotsugae* Hopkins; western balsam bark beetle, *Dryocoetes confusus* Swaine), pathogens (armillaria root rot, annosum root rot), and a plant parasite (dwarf mistletoe, *Arceuthobium* spp.). Although little is known about how these species will respond to climate change, it is reasonable to assume that their impacts will increase in the near to medium term as their host trees undergo stress in response to climate change.

As the climate continues to change, it is likely that both native innocuous and alien invasive species will increasingly contribute to disturbance. Indeed, there is already evidence that the impacts of these types of disturbance agents are increasing. In northwestern British Columbia, dothistroma needle blight (*Dothistroma septospora* (Dorog.) Morelet, caused by a native innocuous species) has caused widespread mortality of lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.) plantations as a consequence of warmer and wetter conditions (Woods et al. 2005). Although it is not known what the direct effects of climate change may be on established alien invasive species such as the emerald ash borer, *Agrilus planipennis* (Fairmair), (Dobesberger 2002) and the brown spruce longhorn beetle, *Tetropium fuscum* (Fabricius) (Smith and Humble 2000) it is likely that their impacts will increase because of stress to their host trees caused by climate change, as outlined above. Moreover, the potential for damaging alien invasive species to become established in the future will be enhanced owing to increased niche availability as a result of a warming environment (Ward and Masters 2007) combined with greater numbers of introductions as global trade increases.

Although disturbance is normal in most ecosystems and not inherently detrimental, impacts that are outside the range of natural variability can result in ecosystem degradation that is self-reinforcing and irreversible (Loehle and Leblanc 1996; Rapport and Whitford 1999). In the longer term (i.e., up to 2100), given additional climate change and elevated disturbances (by fire, biotic agents, and their interaction) that fall beyond the range of natural variability, Canadian forests and the suite of biotic disturbance agents operating in them are unlikely to resemble those with which we are currently familiar. Therefore, the level of uncertainty regarding biotic disturbance will increase dramatically to the point that it will become impossible to predict the magnitude of their impacts (Table 4).

2.3.3 Forest Growth

Table 5 displays a summary assessment of how climate change will affect forest growth for five forested regions in the near term (2011–2040), medium term (2041–2070), and long term (2071–2100). The basis for this assessment is discussed in this section.

Table 5. Qualitative assessment of the scale of impact of climate change on forest growth (productivity), by forest region

Period	Atlantic–Mixedwood	Boreal East	Boreal West	Montane	Pacific	Canada
Now	?	?	?	?	?	?
Near-term (2011–2040)	+	+	-	-	NC	?
Medium-term (2041–2070)	+	++	-	--	NC	?
Long-term (2071–2100)	+	++	--	---	NC	?

NC = no change observed/expected. ? = uncertain. Scale of impact is indicated as follows. Increase: + low, ++ moderate, +++ high. Decrease: - low, -- moderate, --- high.

Forest growth in response to climate change is predicted to be variable across the country and among species. Growth reduction owing to drought in Boreal West and Montane forests is very likely and will be the most dramatic short- to medium-term outcome of climate change. In contrast, modestly increased growth is generally predicted in the east, although it is about as likely as not that we will be able to detect the change outside the range of natural variability for at least the first half of this century. In general, growth increases will be less than would be predicted strictly on the basis of the new climate conditions because of genetic maladaptation of populations of trees to altered environmental conditions (Andalo et al. 2005; Beaulieu and Rainville 2005; Savva et al. 2007). Northward displacement of provenance planting zones can help decrease maladaptation and capture the growth potential offered by the new climatic environments. These predictions do not take into account the impact of increased atmospheric CO_2 concentrations, which may further enhance the growth and reduce the water use of trees (e.g., Norby et al. 2005), nor do they take into account the potential alteration of disturbance regimes or introduction of foreign pests, which may have large impacts on future forest productivity.

The growth response to future climate change will be highly variable within Atlantic–Mixedwood forests because these forests are mixes of species at the northern and southern limits of their current ranges. Stand dynamic processes governing ecosystem responses to disturbances should favor southern species over northern species. For example, the growth of temperate hardwoods such as sugar maple should be enhanced, whereas that of balsam fir should decline at the southern end of its range, mostly because of balsam fir's intolerance to drought (Goldblum and Rigg 2005). However, some southern species that will be well suited to the changed climate currently have only a minor presence in the regional forest, limiting their capacity to take advantage of changed growth circumstances for the foreseeable future. In contrast, planting trees and tending young, naturally regenerated stands are widespread practices in these regions, providing opportunities for forestry practices to supplement natural stand dynamic processes to hasten the transition to a forest that is better adapted to the changed climate. During the transition period it is expected that insect disturbances and extreme weather events (e.g., hurricanes and midwinter thaws) will reduce growth and inventory more than in the past.

The current west-to-east rainfall gradient in the Boreal East forest is predicted to be largely maintained under climate change, with the result that the most significant drought limitations to growth are forecasted for northwestern Ontario's forests (Parker 1998). In general, the growth of most species will increase with increased temperature. However, realized growth will not be as great as potential growth because of genetic maladaptation to the new conditions. Species at the southern ecotone, sugar maple in particular, may see a substantial increase in growth and potential climatic range expansion by 2041–2070, whereas drought-intolerant balsam fir may have reduced growth in the southern portion of this zone.

In general, tree growth in the boreal forest adjacent to the Prairies (the Boreal Plains ecozone) is expected to decline owing to increased water stress, as dry parkland conditions are expected to extend north in this ecozone as well as in the Peace and Mackenzie river valleys by 2041–2070 (see Figure 7 and Hogg and Bernier 2005). Tree growth may increase, however, in areas at higher elevation such as the hills of northern Alberta and near the Saskatchewan–Manitoba border, where much moister conditions prevail (Hogg 1994). Growth of balsam fir and white spruce is not predicted to increase in the middle of the century (Girardin et al. 2008) in spite of higher temperatures, again because of drought limitation. In general, it is likely that tree growth north of the Boreal Plains, currently limited by cold temperatures, will increase, but negative impacts may be expected in climatically dry, northern outliers such as the southwestern Yukon (Hogg and Wein 2005).

In the Montane region, the climate varies strongly according to elevation, from warm and dry in the lowlands and valleys to cold and wet in higher areas. As in the Boreal West region, the area of forests under drought stress is expected to increase, especially in low-elevation areas of interior British Columbia and along the foothills

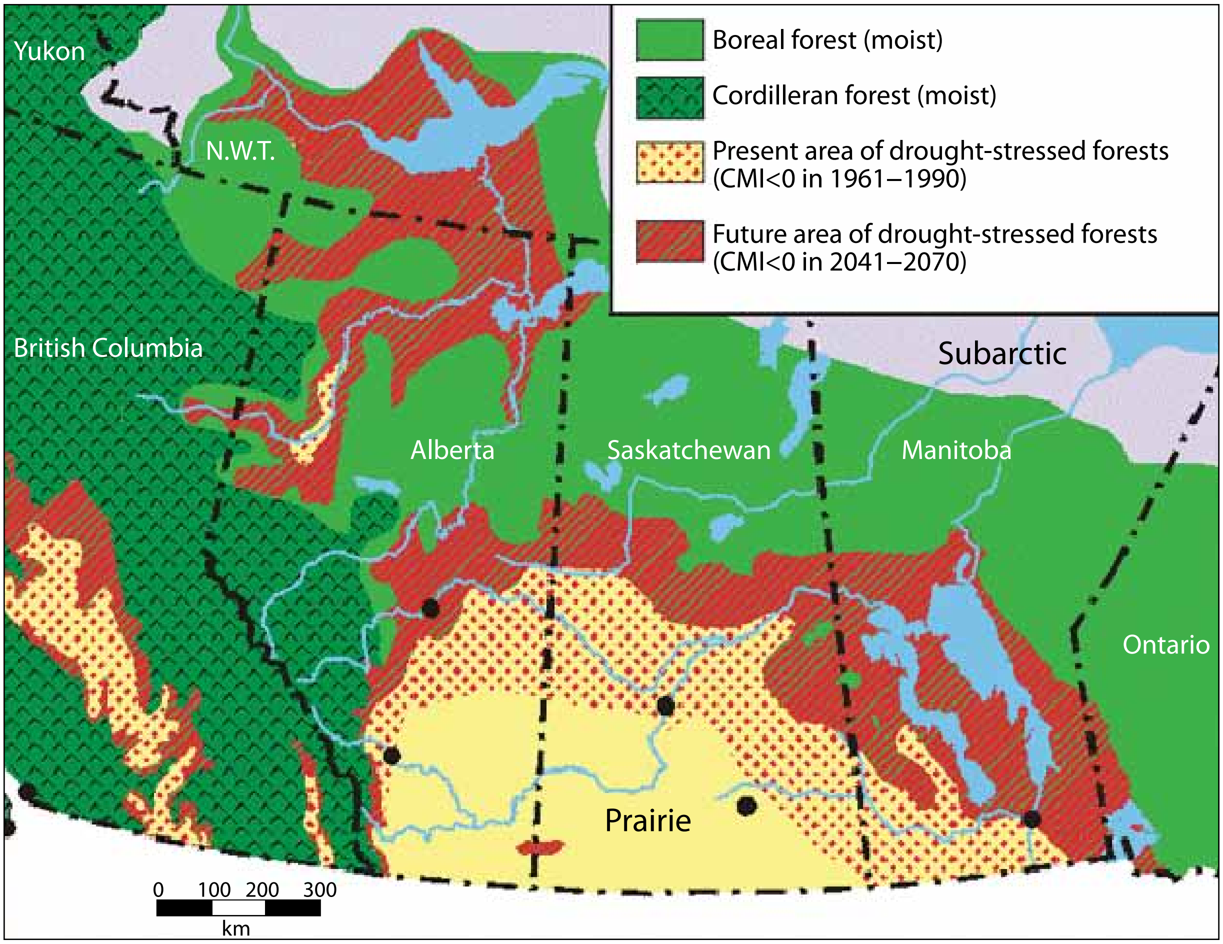

Figure 7. Distribution of drought-stressed forests in the western Canadian interior under observed recent climate (1961–1990) and under a projected future climate scenario for 2041–2070 (CGCM2–A2). Drought-stressed forests are defined as those areas where average precipitation is insufficient to meet the potential water demands (evapotranspiration) of productive forests. CMI = Climate Moisture Index, CGCM2–A2 = Canadian Second-Generation Coupled Global Climate Model with the A2 scenario in which the rate of increase in global greenhouse gas emissions is comparable to the rate of increase in the 1990s. Adapted from Hogg and Bernier (2005) with permission of Canadian Institute of Forestry.

of southern Alberta (Fig. 7). Lodgepole pine constitutes a major proportion of the commercial forests in this region, and its overall productivity has already undergone a dramatic, climate-related collapse as a result of the ongoing regional outbreak of mountain pine beetle (e.g., Carroll et al. 2004). In areas that escape the impacts of this insect, lodgepole pine productivity is predicted to increase in response to temperature increases of up to 2 °C or 3 °C, but studies show either a continued increase (Monserud et al. 2008) or a decline (Wang et al. 2006) in productivity with further temperature increases. All studies agree, however, that the landscape-level productivity of lodgepole pine will decrease dramatically if temperatures increase more than 3 °C because the range of this species will shrink as a result of increased drought. Evidence also shows a decoupling of growth response and climate at the northern limits of the range of lodgepole pine, suggesting a lack of equilibrium between the range and current climate in these areas (Rehfeldt et al. 1999; Johnstone and Chapin 2003) and therefore a likely absence of a maladaptation response. This means that local populations at the northern limit of lodgepole pine could still be "southerners" genetically speaking and therefore better adapted to warmer conditions in the future.

Finally, it is likely that the response of Pacific coastal forests to climate change will vary by species. A general analysis of climate sensitivity by species revealed that those with broader ecological ranges were more likely to benefit or at least not suffer from detrimental effects

than specialist species whose growth was more closely bound to narrow ranges of environmental conditions (Laroque and Smith 2005). Lowland temperate coastal species may be stressed through the loss of their chilling requirements, whereas midaltitude coastal species may see their productivity enhanced (Burton and Cummings 1995).

2.3.4 Forest Succession

From paleobotanical studies, the generally accepted value of migration speed for tree species is 50 km per century, although recent genetics studies suggest the presence of interglacial refugia for tree species and therefore possibly even slower rates of range expansion (McLachlan et al. 2005; Anderson et al. 2006). Climate change will move isotherms northward by about 300 km for each 2 °C increase in annual mean temperature, with a corresponding northward shift in the climatic habitats of tree species. Current predictions suggest that a 2 °C increase in temperature could be achieved over the next 50 years in most of Canada (see section 2.2). Such a pace of change clearly outstrips the most optimistic estimates of the migratory ability of tree species, which is probably not more than 5 km per decade, making invasion by new species through natural means unlikely over the next century. Additional human-induced barriers such as forest fragmentation further preclude rapid migration of tree species.

As a result, without human intervention, forest change will involve a gradual shift in dominance among species already present within the forest matrix rather than an invasion by new species following mortality of the species that are currently present. For example, in New Brunswick a decline in the abundance of balsam fir and the spruces may be accompanied by an increase in the abundance of hardwoods and birches (*Betula* spp.) that can tolerate northern climate conditions. Such competitive displacement through gap dynamics could be very slow, taking place on scales of centuries, unless accelerated by disturbances or extreme climatic events. It is generally accepted that disturbances drive forest dynamics (Oliver and Larson 1996) by freeing growing space for regeneration. Large stand-replacing disturbances are most common in the fire-prone portions of the boreal forest, whereas small-scale gap-generating disturbances are most common in the moister forests of the Pacific Maritime region, in the Atlantic–Mixedwood region, and in the boreal forests of eastern Quebec. Large-scale disturbances will provide the most dramatic impetus for species changes, as they tend to favor pioneer species (Loehle 2003). Species that are able to regrow vegetatively following drought and fire, such as aspen and birch, may outcompete conifers when hot, dry conditions prevent successful establishment of seedlings (Price et al. 2001). The conifer cover may also be dramatically reduced when the interval between successive fires is too short to permit sexual maturation of trees. Such local changes may occur very rapidly, over the course of a few decades. Examples of such shifts are found in the southern lichen woodlands of the eastern boreal forest (Payette et al. 2000).

In general, climate-sensitive species will tend to decline relatively more rapidly but will only slowly be replaced by more climate-tolerant species; hence, rapid changes in climate will gradually lead to species impoverishment at local scales. This will also affect other plants and animals that depend on particular tree species for their habitat, thereby contributing to a general loss of biodiversity. It is generally believed that forest composition will be more resilient to climate change in the central portion of species' ranges (Chapin et al. 2004). In all regions, human-aided species migration may be used to take advantage of new climatic environments. Maps of climatically suitable ranges for most of Canada's species under current and projected climates are available at http://www.planthardiness.gc.ca/.

It is likely that boreal softwoods will be extirpated from the southern edge of their distributions in eastern Canada. For example, the range of drought-sensitive balsam fir is likely to be strongly reduced in the lowlands of the Atlantic Maritime ecozone but stay untouched in the Appalachian portions of that ecozone. In contrast, temperate hardwoods like sugar maple may gradually expand into the boreal forest (Goldblum and Rigg 2005), but this expansion should take centuries unless it is aided by human intervention. As mentioned above, changes in disturbance regimes, especially in the western part of the Boreal East region, may favor pioneer species such as white birch (*Betula papyrifera* Marsh.) and aspen.

Significant changes are expected to occur in the boreal plains and taiga plains areas of western Canada, where black spruce will be replaced by drought- and fire-tolerant pine species (*Pinus* spp.), whereas the mixedwood forests of these areas are less likely to undergo compositional change (Burton and Cummings 1995). At the southern edge, in regions already dominated by relatively drought-tolerant species (jack and lodgepole pines and aspen), even slight increases in the frequency or intensity of drought, wildfires, or attacks by insects (e.g., mountain pine beetle; large aspen tortrix, *Choristoneura conflictana* (Walker); forest tent caterpillar) could be sufficient to cause localized losses of forest cover.

Lodgepole pine is expected to be extirpated from a significant portion of its southern range in Alberta (Monserud et al. 2008) and probably also from portions of interior British Columbia. Species that live in elevation bands in mountains are also predicted to lose suitable habitat quickly. In contrast, range expansions are predicted for Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco var. *menziesii*) and ponderosa pine (*Pinus ponderosa* Dougl. ex P. & C. Laws.) in interior British Columbia (Hamann and Wang 2006). Finally, climate analysis suggests an expansion of Pacific coastal ecozones as a result of climate change (Hamann and Wang 2006) and, more generally, major changes in climatic habitat across the entire ranges of some species (McKenney et al. 2007). This suggests that environmental stress and disturbances resulting from climate change are likely to cause a major change in species composition in the coming decades.

2.4 What Are the Expected Future Impacts on Canada's Forest Sector?

2.4.1 Timber Supply

The impacts of climate change on the forest as described in the previous section will affect both biophysical and economic aspects of the timber supply in Canada in a wide variety of ways, with the magnitude and type of effect in any given region dependent on the climate change in that region. There will be effects on the quality and quantity of timber and the quantity and location of salvage.[3] Table 6 displays a summary assessment of some of the impacts of climate change by forest region now and in the near term (2011–2040), medium term (2041–2070), and long term (2071–2100).The basis for this assessment is discussed in this section.

Most of the wood that will be harvested in Canada over the next 50 to 100 years will come from trees that are already growing or from those that will be planted in the next decade, with minimal consideration of climate change impacts. As described in section 2.3.3, in

Table 6. Qualitative assessment of the scale of impact of climate change on timber supply (considering quantity, quality, and timing), by forest region

Period	Atlantic–Mixedwood	Boreal East	Boreal West	Montane	Pacific	Canada
Now	NC	+	+	+++	NC	++
Near-term (2011–2040)	+	-	+	+	NC	+
Medium-term (2041–2070)	+	-	--	--	+	-
Long-term (2071–2100)	+	-	-	-	+	-

NC = no change observed/expected. Scale of impact is indicated as follows. Positive: + low, ++ moderate, +++ high. Negative: - low, -- moderate, --- high.

[3]Gilsenan, R. 2007. Scoping paper on potential implications of climate change for timber supply in Canada. Nat. Resour. Can., Can. For. Serv., Policy, Econ. Ind. Branch, Ottawa, ON. Draft paper.

some areas there will be an increase in forest productivity owing to climate change, whereas in other areas there will be a decrease. Thus, a gradual warming of the climate may enhance the long-term supply of timber in some areas. This perspective, however, fails to take into account the impacts of natural disturbances. As shown earlier, wildfires, insect infestations, and drought will increase in many regions of the country, resulting in short-term increases in the supply of salvage material, which in turn will translate into medium- to long-term decreases in overall timber supply through the impacts of disturbances on certain age classes of trees. Any improvements in productivity resulting from enhanced growth because of climate change will probably not be able to offset the productivity that will be lost because of increased natural disturbances (Kurz et al. 1995). For this reason, Kurz et al. (2007) suggested that the carbon stocks in Canada's boreal forest are very likely to decline as a result of climate change. Although these authors did not look at timber supply, their results can be extrapolated to suggest that timber supplies will probably also decline.

Further complicating this picture in the longer term, bioclimatic zones and the tree line will shift north, as outlined in section 2.3.4, allowing southern species to expand their ranges north. This will have an impact on ecosystems in general and future wood supply flows in particular. In the very long term, the species mix of forests will change as a result of forest competition and succession, which in turn will change the species composition of fiber supply, with implications for products and markets. This shift in species mix may increase growth rates in some areas and may allow the introduction of faster growing species, eventually increasing timber supply. Faster growing hardwoods, for example, may do better (Spittlehouse 2005) under climate change than they do at present in many regions. This trend will affect not only forest management decisions for existing forests (e.g., thinning) but also planning for future forests in terms of species selection.

A warming trend in areas east of the Prairies increases the likelihood of drought, fire, disease, and more severe outbreaks of pests, notably the eastern spruce budworm, (*Choristoneura fumiferana* (Clemens), depending on the impacts of climate change on complex prey–predator relations. However, this increase in natural disturbances could be partially offset by increases in growth rates accompanying higher atmospheric CO_2 levels, higher temperatures, a longer growing season, and increases in precipitation in some areas of northeastern Ontario and western Quebec, which could significantly increase productivity and timber supply in those areas (Colombo and Buse 1998). The net effect of these impacts is difficult to predict (as described in section 2.1.2). In northwestern Ontario, in contrast, an increased incidence of drought and severe disturbances could have serious consequences for the timber supply. A predicted reduction in precipitation in this area could trigger severe pest outbreaks and forest fires (Colombo and Buse 1998). Similar effects, although perhaps less severe, may also occur in southern Ontario.

The impacts of climate change on timber supply are expected to be greatest in the short and medium term in the Boreal West region because of increased disturbance regimes (fire, pests) and drought. Increases in forest, grassland, and crop productivity as a result of higher temperatures and higher atmospheric CO_2 concentrations could therefore be limited or offset by decreases in productivity because of reduced available soil moisture, and dry soil is more susceptible to degradation. Both the quantity and quality of fiber supply from aspen are expected to decline in the southern Boreal West region owing to increasing impacts of drought, insects, and fungal pathogens. The zone of greatest aspen productivity is likely to move northward (or upward) into more remote areas, posing challenges for the industry in terms of timber access and transportation costs.

In British Columbia, a large increase in the amount of salvage material as a result of outbreaks of the mountain pine beetle has translated into an increase in supply in the short term, but in the medium to long term such outbreaks are expected to negatively affect timber supply because large amounts of timber are killed earlier in the timber's growth cycle than it would otherwise have been harvested. As

described in section 2.3.2, large-scale outbreaks of pests such as the mountain pine beetle and spruce beetle are expected to persist and expand with continued warming. The spread of the mountain pine beetle is a growing concern east of British Columbia, especially in Alberta, with localized infestations already occurring east of the Rockies. There is particular concern that the beetle infestation, which until now has been confined mostly to lodgepole pine forests, could migrate to jack pine stands in the boreal forest (Johnston et al. 2006; Carroll et al. 2007), which extends across the northern Prairies and eastward across Canada, causing supply effects similar to those currently being experienced in the Montane region of British Columbia.

All of these factors combined will directly affect the variability of timber supply, the costs of mitigation and adaptation, and the nature of adaptation responses and will have downstream implications for mill operations, in terms of both cost and capacity, and their location. Table 7 shows how various impacts of climate change are expected to affect the quantity and quality of timber supply in Canada and international supply and demand in the future.

2.4.2 Forestry Operations

Climate change will affect forestry operations and practices such as the timing of harvesting and road building. Table 8 displays a summary assessment of some of these impacts by forest region now and in the near term (2011–2040), medium term (2041–2070), and long term (2071–2100).The discussion below provides the basis for this assessment.

In response to increased winter-kill and insect-caused weakness and because of forest managers' desire to reduce forests' susceptibility to insects and fire, there will probably be an increase in selective logging, thinning, and fuel management. In response to more frequent and intensive drought (e.g., in western boreal forests), harvesting levels could be reduced and practices altered to intensify thinning and increase spacing, thus reducing water stress.

In general terms, northern regions are likely to face a series of impacts quite different from those in the rest of Canada. Changes in the length and climate of the seasons will affect harvesting practices. The length of the snow season and snow depth are very likely to decrease in most of Canada. Melting permafrost is expected to become an increasingly important issue, because the resulting softer ground will affect access (and potentially site quality). Shorter, warmer winters will reduce the life and usefulness of winter roads, which will also cause access problems and increase infrastructure costs. A decrease in winter harvesting because of these problems, along with increasingly restricted summer harvesting owing to increases in fire danger, will mean a shorter harvesting period, potentially reduced harvest, and, more importantly, significant increases in wood costs. Changes in the timing and volume of peak flow in streams (e.g., increased runoff) may cause road failures and affect other infrastructure such as buildings, which will in turn also affect the practices used to build roads and other infrastructure and the associated costs.

Water shortages, which have already been documented in the Boreal West region and northwestern Ontario, are projected to become more frequent as summer temperatures and evaporation rates increase, negatively affecting irrigation and processing costs. As discussed previously, drought conditions also increase the risk of other natural disturbances such as fires or insect infestations.

Large natural disturbances, such as the mountain pine beetle infestation or increases in fire activity, have the potential to create a large amount of material that needs to be salvaged if value is to be derived from the dead timber. This increase in salvage material, in turn, creates a host of challenges for infrastructure and forest management, including difficulties in accessing fallen timber, problems with industrial capacity to process the increased volume, transportation issues for moving the large volume of dead or processed timber, and market-access problems during high supply periods.

Current manufacturing technologies for pulp and wood products may not be optimal given the changes in the timber supply that are expected in the future (in terms of salvage, species changes, timing, and quality), as evidenced by the current problems processing salvage material in British Columbia (Spittlehouse 2005; Ogden and Innes

Table 7. Examples of climate change impacts on timber supply over time

Issue	Range of impacts that affect timber supply		
	Short term (10 years or less)	Medium term (up to 50 years)	Long term (beyond 50 years)
Quantity of timber supply			
Extreme weather events (EWE)	Increases in supply of salvage due to increases in EWE – capacity problems.	Local to regional reduction in timber supply.	Changes in species composition toward tolerant species, or species with life cycles commensurate with disturbance frequencies (e.g., fast growing hardwoods instead of softwoods). Changes in age structure of the forest toward younger age classes. Greater unpredictability leads to greater uncertainty.
New disturbance agents, changing disturbance regimes	Increase in salvage supply.	Species maladapted to disturbance agents or regimes. At the local scale, possible severe reduction in supply due to lack of mature stock caused by major disturbances in the past.	
Warming	Local to regional impacts on yield in short term. Significant mortality (e.g., due to drought).	Change in local site quality indices: dry sites may get lower ratings, cool and wet sites better ratings. Change in species composition, especially in transitional zones and species' outer range limits.	Changes in local to regional supply patterns brought about by combinations of changing yields and site indices.
Species composition	No impact in short term, but managers might proactively diversify planting stock.	Higher frequency of large-scale disturbance may speed species replacement, especially if stock is replanted. Small impacts on yield possible as more appropriate species are introduced.	Changes in species composition will affect yield, accessibility, mill location.

Table 7. Concluded.

Issue	Range of impacts that affect timber supply		
	Short term (10 years or less)	Medium term (up to 50 years)	Long term (beyond 50 years)
Quality of timber supply			
Insects	Decrease in quality brought about by damage caused by insects such as the mountain pine beetle.	Lower fiber quality if immature timber is harvested. Reduction in the supply of mature timber, due to previous infestations.	Local to regional: changing nature of fiber due to new species composition.
Warming	Changing fiber quality where productivity or survival is affected. Rapid increase in growth rates may negatively affect fiber quality, and vice versa.	Changing fiber quality where productivity or survival is affected. Rapid increase in growth rates may negatively affect fiber quality, and vice versa.	Early adaptive action may see species trials that introduce poor stock, affecting overall timber quality. Changes in species composition will change product mixes, potentially eroding some areas of competitive advantage and introducing new ones.
International			
Supply	Short-term increases in salvage material may affect prices regionally.	Increases in growth rates and diversification into other product markets may open other opportunities, but a reduction in timber supply in the mid-term may reduce supply.	Increases in growth rates and diversification into other product markets may open other opportunities.
Demand	Short-term shocks to foreign supply and demand due to EWEs like hurricanes may increase demand internationally.	Decreased competition from drought conditions in the tropics potentially offset by increases in production elsewhere.	Decreased competition from drought conditions in the tropics potentially offset by increases in production elsewhere.

Table 8. Qualitative assessment of the scale of impact of climate change on forestry operations, by forest region

Period	Atlantic–Mixedwood	Boreal East	Boreal West	Montane	Pacific	Canada
Now	NC	-	-	---	NC	--
Near-term (2011–2040)	NC	-	--	-	NC	-
Medium-term (2041–2070)	+	-	-	+	-	-
Long-term (2071–2100)	+	-	-	+	-	-

NC = no change observed/expected. Scale of impact is indicated as follows. Positive: + low, ++ moderate, +++ high. Negative: - low, -- moderate, --- high.

2007a). An increase in the use of salvage material will also reduce average fiber quality. Moreover, an increased reliance on lower quality fiber has implications for the products that can be produced and the markets for those products and will also increase the costs associated with processing. For example, some mills in British Columbia have had to install new equipment to process harder, drier salvage timber killed by the mountain pine beetle, as they can no longer assume that logs will cut nicely. Moreover, the shelf life of salvaged timber is proving to be shorter than originally anticipated, which has affected the amount that can be economically salvaged. Decision-makers who are considering investing in increased mill capacity to process a greater supply of salvage material will have to consider the longer term availability of a suitable timber supply to determine if such investments are worthwhile. Such temporal issues will pose some of the greatest challenges to our ability to adapt effectively to climate change.

In the longer term, changes in productivity and species mix will affect harvesting, processing, and planting practices by affecting rotation ages, species selection, wood quality, wood volume, size of logs, and infrastructure development. Any increases in supply in northern areas, for example, will necessitate an associated increase in processing equipment and transportation routes.

Moreover, international yield models indicate that climate change might increase global timber production, driving down global prices and affecting supply and demand flows in international and regional markets (Kirilenko and Sedjo 2007). This will create both market opportunities and market dangers for sellers and buyers alike, particularly in emerging markets such as biomass energy. Industry participants who recognize these changes early will be most likely to benefit from changing climate and market conditions.

2.4.3 Resource-based Communities

Remote and resource-based communities, including Aboriginal communities, have already been affected by climate change. These communities are vulnerable to drought, ice-jam flooding, forest fires, the absence of late spring frost, and warmer winter temperatures, which have resulted in repeated evacuations, disruption of vital transportation links, and stress on forestry-based economies. Projected increases in winter temperatures will further shorten the operating season of winter roads, which will limit the delivery of construction materials, food, and fuel to many far northern communities, including mine sites.

An increased frequency of forest fires and forest pest outbreaks is expected to negatively affect the health and economic base of communities dependent on the forest industry, particularly in the far northern sections of the country. Water shortages represent perhaps the greatest threat to areas such as the Boreal West region, with drought conditions affecting communities' water supply and tourism revenues. Beetle damage is expected to have a positive impact on nearby forest-dependent communities in the short term, owing to initial increases in the amount of salvage material, but a negative impact in the medium to long term, owing to subsequent decreases in timber supply.

In addition, local economies will face both opportunities and challenges as they are exposed to structural changes in global markets resulting from responses of the global timber supply to numerous factors including climate change (Williamson et al. 2006, 2007). The speed with which mill investors are able to respond to changes in demand for, supply of, and prices of timber will strongly affect industry competitiveness and end-product price behavior (Irland et al. 2001).

Increases in natural disturbance events such as fire will result in a need to increase the resources used to protect communities and other areas with high economic and social value. The increased demand for firefighting services will have to be balanced against the fact that such services are funded by government tax revenues and resource rents, which will also be affected by the impacts of climate change (Ohlson et al. 2005). Changes in timber supply will also affect rent values and land-use options for landowners and may increase land-use conflicts (Lemmen and Warren 2004).

2.4.4 Nontimber Forest Uses and Values

In addition to providing market benefits, forests have ecological, aesthetic, cultural, and heritage value. Climate change will have impacts on the ecosystem services provided by Canada's forests, including carbon storage, air and water purification, windbreaks, wildlife habitat and biodiversity, medicinal plants, nutrient cycling, and erosion control (Columbia Mountains Institute of Applied Ecology 2005). Warmer and drier summers, for example, will affect streams and the adequacy of current riparian protection requirements. Snowpack loss is expected to affect water supply in many areas of the country. Decreases in the size of glaciers, decreases in snowpack, shifts in the timing and amount of precipitation, and prolonged drought are expected to increasingly affect the water supply in the Montane region. In that region, major hydrological and ecological changes are already expected in pine-dominated watersheds as a result of substantial increases in logging activity to salvage beetle-killed timber.

Biodiversity

Wildlife and habitat will be affected by new insects and diseases, forest fires, and changes in tree species. Northward migration of species along with competition from invading species will affect ecosystems, although more research is needed on the timing of these effects (Scott and Lemieux 2005). Research to date has shown that rising temperatures and changes in precipitation and drought patterns have already begun to affect some species (Varrin et al. 2007), with the ranges of mobile species, such as flying insects and birds, and generalists, such as raccoons, already shifting to the north.

The ability of individual species to adapt to climate change will depend on their ability to disperse across the landscape and regenerate themselves, the species richness available for selection and development of future communities as these communities reassemble themselves, and the genetic variation within the species, which forms the basis for the natural (or human) selection upon which their evolution in response to changing environments is based.

Displacement and colonization will happen at the species level, with different species having different ranges of habitat tolerance and different potential speeds of displacement. Thompson et al. (1996), for example, predicted that wildlife species responding at the landscape level (i.e., those with body sizes greater than 1 kg) will be most affected by the impacts of climate change, with species such as moose (*Alces alces* (Linnaeus, 1758)) and caribou (*Rangifer tarandus caribou* (Gmelin, 1788)) expected to decline significantly across Ontario and Quebec, although species such as white-tailed deer (*Odocoileus virginianus* (Zimmermann, 1780)) are likely to become more abundant.

Parks that were established to protect individual species, such as Woodland Caribou Provincial Park in Ontario, may no longer meet their protection objectives under a rapidly changing climate (Lemieux et al. 2007). However, these protected areas will encompass new, evolving ecosystems that will probably represent change in the ecodistrict or ecoregion.

Although the cumulative impacts on biodiversity are difficult to predict, it seems clear that there will be "winners" and "losers" and that we may have to rethink concepts associated with habitat management and the preservation of biodiversity.

The dispersal of individual species will be limited by the availability of migration corridors, suitable habitat, and the movement of forage and prey (Inkley et al. 2004), and species that require a narrow range of temperature and precipitation conditions will be at greater risk of maladaption or extinction (Varrin et al. 2007). Similarly, the soil properties of new habitats may be inappropriate for some species.

The impacts of drought conditions are expected to be especially visible in isolated island forests and forest fringe areas along the northern edge of the Boreal West, where permanent losses of tree cover are most likely to occur, leading to losses of habitat for wildlife, recreation, and other nontimber values (Henderson et al. 2002). Such changes would also have far-reaching implications for biodiversity in these areas, through both the extirpation or extinction of existing species and the arrival of new species (including exotics).

Indeed, these shifting conditions are likely to introduce new pests and diseases, further affecting ecosystems, forest resources, and some human populations. Forest intraspecies and interspecies relations are complex and therefore difficult to predict. However, it seems certain that new communities will assemble, within which negative interactions are possible.

The diversity of tree species in Canada's forests is expected to be affected by climate change. Thompson et al. (1996) have predicted that the combination of increasing temperature and more fires will result in shrinkage of the area covered by the boreal forest toward the north and east of central Canada, with species that do relatively well in fire-dominated landscapes becoming most common, especially jack pine and aspen. They predict that patch sizes will initially decrease, then expand, resulting in considerable homogenization of forest landscapes, with little old-growth forest in the future. If climate change occurs as rapidly as is predicted, then some species, particularly those with heavy seeds, may not be able to respond to the rapid changes, and local extinctions can be expected, with forests dominated by white pine in the south and black spruce in the middle north becoming less common (Thompson et al. 1996).

As the climate changes, biodiversity will likely become impoverished in many areas, with loss of biodiversity seriously constraining natural selection and consequently the capacity of individuals and species to colonize new habitats and their capacity to adapt to new conditions. The tundra ecosystem, for instance, contains plants and animals that are uniquely adapted to their northern climate and short growing season. These plants are adapted to the summer high light levels and winter darkness of Canada's North, and they take advantage of the brief period when the shallow, nutrient-poor soils that overlie permafrost, or poorly drained peat soils, are warm enough to permit growth. These plants may not be able to adapt to the transformation in the functioning of their ecosystem that would result from loss of permafrost.

Ecosystem Services

Water shortages represent perhaps the greatest threat to areas such as the Boreal West, with drought conditions affecting ecosystems and tourism. Indeed, virtually all aspects of ecosystem functioning would be disrupted by a shift toward drier, more prairie-like conditions in this region (see Fig. 7). For example, aquatic systems, water-based recreation, and fisheries in the southern boreal forest would be profoundly affected by lowered lake levels, stagnation, eutrophication, and algal blooms during periods of drought (Schindler and Donahue 2006), along with associated increases in lake salinity (Michels et al. 2007). Peatlands such as bogs and fens are common in the western boreal forest but are absent from the prairies, as they depend on moist climatic conditions to sustain consistently high water tables. Under climatic drying, peatlands and associated forest cover types (black spruce and tamarack) in the southern boreal forest would either degrade gradually through increased rates of peat decomposition or be transformed rapidly (with large losses of carbon) following deep, peat-burning fires.

Moreover, the downstream impacts of a changing climate and its interaction with other factors (air pollution, harvesting, fire, etc.) are also likely to increase. For example, the Millennium Ecosystem Assessment (2005) predicted that, at a global scale, freshwater ecosystems have the highest proportion of species threatened by extinction owing to climate change. Reduced growing-season low flows caused by climate change will mean that streams will likely have less water and fewer nutrients to support existing aquatic ecosystems. Other effects are possible as well. For example, stream sulfur levels have been increasing recently in some areas of Ontario (Schiff et al. 2005; Eimers et al. 2007) owing to drought, even though sulfur deposition continues to decline. However, another potential mechanism that can cause an increase in sulfate release is declining acidity (increasing pH) in soils, which changes the adsorption dynamics of sulfate and increases the sulfate available for export (Foster and Hazlett 2002). At this point, the relative contributions of the two mechanisms are not clear.

Carbon

Because of its influence on forest growth, decomposition, and disturbances, climate plays an important role in the forest's carbon balance and its contribution to the global carbon cycle. Climate therefore affects the distribution of carbon in biomass, dead organic matter, and soils. As the climate warms, for example, forests are expected not only to grow faster in some areas but also to store a higher proportion of their carbon in living biomass (as opposed to dead organic matter). Moreover, carbon uptake levels and decomposition rates vary with temperature and precipitation, as do rates of natural disturbances that can cause carbon losses over large regions (Kurz et al. 2007). Canada's managed forest was a net carbon sink for most of the 1990–2005 period, but projections for the 2006–2022 period found that it very likely will be a net source of greenhouse gases because of the current mountain pine beetle infestation, an expected spruce budworm outbreak in eastern Canada, increased salvage logging, and the ongoing risk of fire (Kurz et al. 2008). However, this assessment did not directly account for the impacts of climate change on forest carbon. It is known that fire has been a primary driver of the carbon balance of Canada's forest (Kurz and Apps 1999; Bond-Lamberty et al. 2007), and it is anticipated that the losses of forest carbon brought about by increases in natural disturbances related to climate change (largely wildfires: see section 2.3) will more than offset any increases in growth rates resulting from warming or other impacts of climate change (Kurz et al. 1995, 2007, 2008). Add to this the carbon that is expected to be released through the warming of peatlands (see section 2.3.1), and it seems likely that carbon storage in Canada's forests (managed or unmanaged) will decrease for some time to come. Thus, there is a need to consider what actions could be taken in the managed forest to reduce emissions or increase sequestration to mitigate climate change, beyond any actions that might be taken to adapt to climate change. Ideally, the two sets of actions will be complementary.

Parks and Recreation

Parks and protected areas, which provide valued recreation opportunities and serve important habitat conservation and heritage aims, may face particular challenges if it is not possible to maintain existing natural species and ecosystems in a given area. Protected areas may no longer support the ecosystems they were established to protect, resulting in the dislocation of parks and natural areas (Lemmen and Warren 2004; Scott and Lemieux 2007). Moreover, the duration of recreational seasons will change, with winters becoming shorter and summers longer, which will affect revenues from tourism and recreation.

The effects of climate change on tourism destinations are already evident. In the dry southern interior of British Columbia, for example, drought and forest fires have recently resulted in temporary closures of many major transportation routes and destroyed orchard and winery crops in the Okanagan and North Thompson valleys. Tourism in British Columbia is expected to suffer, particularly in relation to winter sports, as snowpack is lost. In contrast, Browne and Hunt (2007) anticipate that climate change will have a net positive effect on nature-based tourism and outdoor recreation activities in Ontario. They attribute this positive effect primarily to a lengthening of the season for warm-weather activities, which have much higher participation levels than do snow- and ice-based activities.

3. WHAT IS THE RANGE OF ADAPTATION NEEDS?

Climate change will pose significant challenges for sustainable management of Canada's forests for the foreseeable future. Adaptation to climate change occurs autonomously in natural systems. From the perspective of management, however, adaptation involves deliberate efforts to moderate potential damages or benefit from new opportunities (Smit and Pilifosova 2001). There will be economic benefits in some areas of the forest sector, especially at relatively low levels of climate change, so one challenge will be to identify and optimize these opportunities. Negative impacts on the forest, however, could be significant and could increase over time, especially at higher levels of climate change, so the greatest challenge is likely to be determining how to minimize this damage. Higher costs in the future could be avoided with early action.

Although dramatically rapid on a geological time scale, current and projected climate change is a slow phenomenon on the human time scale, making clear detection, understanding, and adaptation to its impacts on forests a long-term challenge. At the same time, forest management in Canada typically involves extensive management of forests that grow relatively slowly: this presents a challenge for adaptation because management decisions made today typically have consequences for decades but may not be appropriate for future forest conditions. As well, large-scale forest disturbances linked to climate can occur rapidly. In their efforts to adapt to climate change, forest sector stakeholders will need to reconcile these various time-scale issues through long-term monitoring and research, proactive, flexible, and adaptive management, and rapid response strategies.

Uncertainty is the most significant challenge, but it is not a reason to avoid action. There is uncertainty about how the climate will change, which is compounded when one considers the impacts of climate change on the forest, the potential future state of the forest, the degree of vulnerability of the forest to climate change, and whether current management objectives are appropriate or even feasible. Moreover, the impacts of changing climate will occur in the context of other uncertain future changes (e.g., in pollution, global supply and demand, commodity prices, public values, and policies). Uncertainty is inherent in any planning for the future, but for the most part forest managers have traditionally assumed that current conditions will continue, and they have not taken climatic or ecological uncertainty into account to any significant extent (Spittlehouse 2005; Johnston and Williamson 2007). With climate change, this assumption becomes increasingly questionable the further into the future one's projections extend. For example, road-building guidelines, biodiversity objectives, seed-source requirements, reforestation standards, riparian management guidelines, and a host of other practices, regulations, and policies implicitly or explicitly assume that the climate will not change. The same is true for the creation and management of protected areas; these practices are based on preserving representative ecosystems defined according to current ecological characteristics (Lemieux et al. 2007; Scott and Lemieux 2007). Adaptation will require explicitly integrating increased uncertainty into decision-making at all management levels (Ohlson et al. 2005; Ogden and Innes 2007a).

3.1 How Should Adaptation Decision-Making Occur?

Many specific local, regional, and national adaptation options have been suggested for the forest sector (e.g., Henderson et al. 2002; Spittlehouse and Stewart 2003; Lemmen and Warren 2004; Hogg and Bernier 2005; Ogden and Innes 2007a; Lemmen et al. 2008). Spittlehouse (2005) distinguished between three types of adaptation: actions aimed at societal adaptation, which would tend to be strategic or high level, such as changes in conservation objectives or public expectations; adaptation of the forest, which would include changes in operational approaches, such as species selection, breeding programs, and fire management; and adaptation to the impacts on the forest, which would involve changes in how the forest is used, such as using more salvage, adjusting mill processing technologies to reflect changing characteristics of the timber supply, or changing requirements for the protection of ecosystem values.

Many actions are possible, and determining the optimal set of actions requires a systematic approach to adaptation decision-making, although as yet there is not a widely established framework for doing so in the forest sector (Johnston and Williamson 2007). Climate change imposes the risk of significant negative impacts. Thus, an approach to developing adaptation strategies on the basis of risk management methods has been promoted (Smit and Pilifosova 2001; Ohlson et al. 2005; Parry et al. 2007; Stern 2007; Lemmen et al. 2008). A structured risk management approach to adaptation would involve five steps: defining the adaptation problem, setting management objectives, and establishing performance indicators; assessing current and future vulnerabilities that impinge on the objectives; developing risk management strategies; evaluating and deciding on the best strategy; and implementing, monitoring, and adjusting the chosen strategy. Adaptation strategies developed in this way can be seen as adding a risk management element to sustainable forest management plans (Spittlehouse 2005).

3.1.1 Defining the Problem and Objectives

Decision-making requires clear objectives, which means first defining the key questions or problems related to adaptation. The context of the questions or problems should also be defined, including temporal and spatial scale, degree of uncertainty and lack of information, policy and institutional frameworks, and relevant jurisdictions and stakeholders. Next is a definition of the objectives for the future forest that adaptation is meant to serve (Ohlson et al. 2005), recognizing that current objectives may not be realistic in a changing climate. The objectives must be articulated at a scale relevant to the particular decision-makers but should reflect the values that society wants to obtain from the forest. For example, the objectives could be based on existing criteria and indicators of sustainable forest management used at the national and provincial levels in forest management plans and in certification standards (Lemmen and Warren 2004; Ogden and Innes 2007a, 2007b). The six criteria and indicators of sustainable forest management of the Canadian Council of Forest Ministers (CCFM) relate to biological diversity, ecosystem condition and productivity, soil and water, role in global ecological cycles, economic and social benefits, and society's responsibility (CCFM 2006).

However, the current objectives of sustainable forest management may need to be reoriented owing to climate change. For example, one possibility is to focus objectives on maintaining or increasing the resiliency of the forest in the face of climate change. Resiliency refers to the capacity of the forest, as an ecological system, to undergo change without fundamental or catastrophic disruption of its essential internal structure and functioning. A management approach that attempts to emulate natural disturbance regimes has been suggested as one way to maintain resiliency (Drever et al. 2006). More generally, a focus on resiliency would highlight the importance of maintaining biodiversity and heterogeneity in forest structure.

3.1.2 Assessment of Vulnerabilities

Assessment of vulnerabilities in relation to forest objectives and values is key for adaptation decision-making (Spittlehouse and Stewart 2003; Johnston and Williamson 2007; Williamson et al. 2007). Vulnerability is the extent to which a system is susceptible to damage, in this case from climate change (Smit and Pilifosova 2001), and it can occur at any scale from local to regional to national. It depends on the degree to which the system is exposed to climate change, the sensitivity of objectives, values and uses given that degree of exposure, and the system's capacity to adjust or adapt its characteristics or behavior to cope with the exposure (Ohlson et al. 2005; Johnston and Williamson 2007). It is also influenced by stressors not related to climate change, such as pollution. Adaptive capacity in the forest sector is determined by the socioeconomic and other characteristics of the sector and its participants. These include the degree of flexibility of policy and planning, the distribution and availability of financial resources, technological capacity, human capital and social networks, and risk perceptions (Smit and Pilifosova 2001; Johnston and Williamson 2007; Williamson et al. 2007).

Vulnerability can be assessed for a range of climate change scenarios, taking into account other influences. As already noted, some adaptation to climate change will occur naturally, but planned adaptation can be thought of as

making choices aimed at reducing a system's vulnerability by reducing its sensitivity to climate change, facilitating or increasing its adaptive capacity, and capitalizing on opportunities created by climate change.

3.1.3 Development of Adaptation Strategies

Adaptation strategies should be based on careful consideration of a range of potential actions: various sets of possible responses can then be combined as the basis for alternative strategies (Smit and Pilifosova 2001; Ohlson et al. 2005). These strategies should recognize cumulative impacts, risk, uncertainty, and the needs of stakeholders. Where possible, decision-makers should also seek synergies between strategies designed to adapt to climate change and strategies designed to mitigate climate change by reducing greenhouse gas emissions or increasing carbon sequestration (Parry et al. 2007; Ravindranath 2007).

Mainstreaming is important: the most effective and successful adaptation will result from systematic integration of climate considerations into existing forest planning and decision-making frameworks, as opposed to the implementation of stand-alone policies or programs, although these too will be useful in some circumstances. Actions should occur at the appropriate level, whether strategic or operational (Spittlehouse 2005; Ogden and Innes 2007a). In a strategic forest management plan, for example, adaptation strategies would typically address large areas and long time horizons, often with objectives related to desired future forest conditions. Adaptation in operational plans would detail actions for smaller areas and shorter time frames consistent with the strategic plan. One important benefit of mainstreaming is that it is more likely to avoid maladaptation or increased vulnerability to climate change owing to lack of information about the potential external effects of a given policy unrelated to climate change or owing to lack of consideration of these effects.

It is likely that proactive strategies will be better than reactive approaches because the former may have a better chance of avoiding or reducing negative impacts and vulnerabilities and of seeking out and benefiting from new opportunities (Ohlson et al. 2005). In general, they may be less costly as well. Proactive strategies would include actions now in anticipation of future impacts as well as actions planned for the future (Spittlehouse and Stewart 2003). Anticipatory adaptation is especially important in Canada's forest sector because of long harvesting rotations: ideally, species chosen for planting today will do well in a different climate in the future (Lemmen and Warren 2004). Reactive responses will also be needed, for example, to unforeseen extreme weather or natural disturbance events. Even in these cases it may be possible to develop, in advance, forecasting, planning, and response systems that lessen the impact of such events.

High degrees of uncertainty associated with a changing climate, its impacts, and the vulnerabilities of various systems highlight the potential importance of implementation, where possible, of strategies using principles of adaptive management; this approach explicitly seeks to address uncertainty. This means establishing an iterative process of learning from the implementation of decisions by researching, monitoring, and assessing the outcomes and then adjusting decisions as needed (Murray and Marmorek 2004; Marmorek et al. 2006; Zhou et al. 2008). The intent is to allow management to better and more responsively deal with uncertainties, although adaptive management has its own challenges (Stankey et al. 2005; Marmorek et al. 2006).

3.1.4 Evaluation, Decision-Making, and Implementation

Multiple decision criteria can be used in evaluating alternative adaptation strategies and the trade-offs among them. These include criteria related to uncertainty, economic criteria including efficiency and impact on competitiveness, social criteria such as equity and social impacts, and environmental criteria (Hauer et al. 2001; Ohlson et al. 2005). The best adaptation strategies will deal with uncertainties by seeking to be robust across a range of possible future forest conditions, which requires understanding what that range might be at scales appropriate for decision-making. Other uncertainty-related criteria could be the degree of uncertainty in obtaining the desired objective, the level of risk of severe outcomes, and the degree of future flexibility that a strategy provides.

Economic analysis is valuable for adaptation decision-making, although the economics of adaptation have not received much attention to date (Dore and Burton 2000; Hauer et al. 2001; Parry et al. 2007; Stern 2007). Adaptation will have a cost, but it is a key part of an economically efficient response to climate change, one that seeks to achieve the best outcome for the least investment of resources (Stern 2007). The costs and benefits of alternative adaptation strategies over time should be considered in relation to the costs and benefits of the impacts of climate change, but impact studies have tended to focus more on physical impacts and vulnerability than on economic impacts (Ohlson et al. 2005; Parry et al. 2007; Stern 2007). As well, economic analysis may be complicated when actions aimed at adaptation also serve or impinge on other goals.

Involving the range of forest sector participants will strengthen adaptation decision-making. However, different participants attach different values to forests, have varying levels of knowledge, and will have different perspectives on how best to respond to climate change (Ogden and Innes 2007b). Perceptions of risk and adaptive capacity will also differ. For example, Williamson et al. (2005) found that a group of experienced forest professionals seemed to perceive risks to ecosystems as being higher than risks to forest-based communities. The current difficulties facing the forest industry may make the issue of adaptation to climate change less salient to some people. In a survey of forest practitioners in Yukon and Northwest Territories, Ogden and Innes (2007b) found that factors such as commodity prices, securing capital, timber availability, trade policies, and environmental regulation were often thought to be more pressing issues than climate change, although many of the respondents expected climate change to increase in importance in the future. In contrast, in a survey of people across Canada involved with protected areas, Scott and Lemieux (2007) found that a large majority believe that climate change is an important management issue today. Understanding these types of differences will be important for designing balanced adaptation strategies that will be supported by stakeholders (Spittlehouse 2005; Johnston and Williamson 2007). An analysis of these differences may also suggest where education and dialogue are needed.

3.2 What is the Status of Adaptation in the Forest Sector?

Awareness of climate change as an issue has grown rapidly in the forest sector, helped by the publication of a number of summaries of knowledge about impacts and adaptation in recent years (e.g., a special issue of *The Forestry Chronicle* in September–October 2005; Johnston et al. 2006; Lemmen et al. 2008; Williamson et al. n.d.[4]) and ongoing research by scientists employed by the federal and provincial governments and universities. Adaptation efforts are under way, but for the most part they are focused on improving understanding, providing education, sharing information, exploring adaptation needs, including climate change in planning processes, and increasing cooperation. Some early efforts to implement adaptation actions have been made; for example, some companies have tried to incorporate climate change considerations into their forest management plans (Johnston and Williamson 2007). However, substantial planned and systematic on-the-ground actions in response to future climate change have not yet occurred, in large part because of the complexities and uncertainties involved.

At the broadest level, the CCFM has started to discuss what climate change means for Canada's forest and forest sector. The Innovation Working Group of the CCFM, along with the Canadian Forest Service, held two focus group workshops in early 2007 to discuss adaptation needs and actions in the sector and the respective roles of sector stakeholders. One workshop involved government officials and the other forest industry representatives. The discussions suggested that cooperation and coordination between multiple stakeholders should be the basis for creating a strategic framework for forest sector adaptation. Such a framework could involve several elements: improving knowledge needed for adaptation decision-making (knowledge), developing tools and approaches to help in decision-making (empowerment), developing adaptation policies and plans including performance measures and monitoring mechanisms (governance), and building public understanding (communications).

At its 2007 meeting the CCFM identified adaptation to climate change as an emerging strategic issue for the sector. It has initiated

[4]Williamson, T.; Columbo, S.; Duinker, P.; Gray, P.; Hennessey, R.; Houle, D.; Johnston, M.; Ogden, A.; Spittlehouse, D. n.d. Climate change and Canada's forests: from impacts to adaptation. Forthcoming.

work in this area, starting with a study examining vulnerability and adaptation of major tree species. The CCFM has already undertaken a number of cooperative actions that will help to address the impacts of climate change. In 2005 it agreed on a Canadian Wildland Fire Strategy based on a risk management approach to fire in the face of climate change and other challenges (CCFM 2005). A national forest pest strategy has also been approved in principle by the CCFM (at its 2007 meeting), with work under way to develop an implementation plan that would provide a common risk-analysis framework. Given the profound impacts that climate change will have on natural disturbances in Canada's forests, these strategies can be seen as important proactive responses.

Discussions about adaptation needs are occurring at the national level among a range of sector stakeholders. The Forest node of the Canadian Climate Impacts and Adaptation Research Network operated from 2001 to mid-2007, focussing on helping the forest sector understand the impacts of climate change and options for adaptation. The Forest Sector Sustainability Table, cochaired by Natural Resources Canada and the Forest Products Association of Canada with members from across the forest sector, held a brainstorming session on the topic in 2007. BIOCAP Canada Foundation supported an assessment of adaptation in forest management by a group of government and academic experts and made the following five recommendations to help the forest sector reduce its vulnerability to climate change (Johnston et al. 2006): enhance capacity to undertake integrated assessments of vulnerabilities at various scales; increase resources for basic scientific research related to the impacts of climate change and adaptation; review forest policies, planning, and management approaches and institutions to assess the ability to achieve social objectives under climate change; improve capacity for risk management; and improve communication and networking concerning issues associated with adaptation.

Provincial and territorial governments are also taking action. For example, the government of British Columbia has determined that climate change represents a significant risk to the province's forest resources, and the provincial Ministry of Forests and Range is developing an adaptation strategy (BC Ministry of Forests and Range 2006; Spittlehouse 2008). In 2002 the Quebec government, in collaboration with others, announced the creation of the Ouranos Consortium to develop knowledge about regional impacts and potential adaptation strategies. In Ontario, the Ministry of Natural Resources is implementing a strategy to understand climate change, lessen its impacts, and help the public adjust. It has a substantial body of research under way to inform citizens and policy-makers (e.g., Browne and Hunt 2007; Columbo et al. 2007; Lemieux et al. 2007). Examples of increased awareness and assessment can be found in many jurisdictions.

Regional workshops have been held to explore the impacts of climate change and options for adaptation in specific contexts. In fall 2007 the Canadian Forest Service and the Ontario Ministry of Natural Resources co-organized a workshop for government officials to explore cooperation in filling knowledge gaps and developing adaptation tools (NRCan–OMNR 2007). Another recent example is a Canadian Forest Service workshop to examine the vulnerability and adaptation needs of the forest sector in Atlantic Canada (Fundy Model Forest 2007). Participants from industry and provincial governments identified the following key gaps in the knowledge that the forest sector needs to guide adaptation actions: process models to predict future growth in response to climate change, information that would give the sector the ability to predict changes in forest species composition, information on the best species and genotypes for planting, and information on how insect disturbance regimes will change and what the impacts will be.

3.3 What is Needed to Improve Adaptation in the Forest Sector?

One way to identify adaptation needs is to identify key strategic questions that forest sector participants are asking, such as those shown in Table 9. More generally, the discussions and workshops on impacts and adaptation across the country noted in the previous section and the discussion in this report suggest that the adaptation needs of the sector are as follows: awareness building and debate, improved knowledge, vulnerability assessments, planning frameworks and tools, and coordination and cooperation.

Table 9. Examples of strategic questions raised by climate change for the forest sector

Federal government	■ How will climate change affect the competitiveness of the forest sector and how should the federal government respond? ■ How will climate change affect our ability to meet our obligations under international agreements? How should climate change impacts inform our negotiating positions? ■ What is needed to ensure the relevance and ultimate use of knowledge generated by the federal government on climate change and its impacts on Canadian forests at the national level? ■ Should current management approaches (little intervention) for parks and wilderness areas change?
Provincial governments/ Forest owners	■ Which forest and site types are at greatest risk of not meeting management objectives under climate change? In which ones will it be easier to reach these objectives? ■ How should forest management polices/guidelines/requirements be adjusted to improve adaptive capacity/adaptation? ■ How will climate change affect competitiveness of the forest sector and how should provincial/territorial governments respond? ■ How will disturbance regimes (fires, pests) change and how can intervention strategies be altered to reduce losses and protect human lives? ■ What will be the impact of climate change on timber supply (cost, growth, location, quantity, quality, timing, salvage)? ■ Should current management approaches (little intervention) for parks and wilderness areas change?
Forest managers, industry	■ What will be the impact of climate change on timber supply (cost, growth, location, quantity, quality, timing, salvage)? ■ How will climate change affect mill operations, product mix, and investment decisions? ■ What should we change first in our forest management, planning, and practices? When? ■ Which forest types and site types are at greatest risk of not meeting management objectives under climate change? Which ones will make it easier to reach these objectives? ■ Will climate change impacts make it more difficult to meet certification standards?
Forest-dependent communities, including First Nations communities	■ Might cumulative impacts require a fundamental reconsideration of forest management practices in some areas? ■ How will impacts on forests affect ecological services (e.g., quantity/timing of water supply)? ■ Are our communities more at risk of fires and how can we prepare? ■ How can we prepare for potential changes in forest management activities?

3.3.1 Awareness Building and Debate

Perhaps the most important and overarching need is for a debate about what climate change means for the values Canadians derive from the forest, because climate change has the potential to affect all these values. The forest sector and society more broadly must answer the following key question with respect to adaptation: Should we seek to maintain the current level of values and services from the forest? It may be more appropriate to ask whether we *can* maintain the current level and how this ability varies among the various values and services we derive from the forest. The question of what the objectives of adaptation should be will need to be resolved. It is unlikely that adaptation could address all potential impacts of climate change, and in any case there is no reason to expect that adaptation will fully preserve the values on which we choose to focus. Our demands for forest values and services will need to be brought in line with the degree and types of adaptation that are feasible and the new opportunities that emerge (Spittlehouse 2005). It can be safely predicted that a debate about the values and uses of Canada's forests in a changing climate will be contentious.

A debate will be meaningful only if its participants have an informed understanding of the issues. Thus, there is a need to educate and build the awareness of forest sector stakeholders and the general public about climate change, the risks to the forest and the values we derive from it, the need for adaptation, and potential actions and strategies.

3.3.2 Improved Knowledge

The key to improving knowledge is a long-term vision and commitment to maintain Canada's capacity to detect, understand, and report on the impacts of climate change and to reduce uncertainty in the projection of future impacts. Specific needs include the following:

- Continuation and expansion of scientific research on climate change and its impacts, including an integrated assessment of the cumulative impacts of climate change and other biophysical stressors on Canada's forests (e.g., on natural disturbance regimes, drought, growth, regeneration, and succession)
- User-friendly access to climate-monitoring records and expanded climate monitoring in northern and high-elevation forested areas
- Accessible and regionally detailed scenarios of future climate change that reduce uncertainties about what might happen where and when, given realistic predictions of greenhouse gas emissions
- Enhanced monitoring programs and systems to identify and provide early notice of changes in the forest in response to climate change
- Assessments of potential impacts of climate change on carbon stocks, habitat and biodiversity, and other ecological benefits, including parks and protected areas
- Scenarios of impacts on timber supply and implications for use of salvage, product markets, mills, and communities
- Scenarios of impacts of climate change on the competitiveness of Canada's forest-products industry, given that the impacts on forests may be different in other countries
- Assessment of other social and economic impacts, such as on First Nations communities, recreation, and tourism

Increasingly, the sector will also need better information about potential forest management options for adapting to climate change. Pilot projects and demonstrations that provide on-the-ground experience would be very useful, as would examples of adaptation to other types of disruptive events. Much could be gained by drawing on the experiences of others nationally and internationally. All such information needs to be synthesized and disseminated at scales relevant to enhancing awareness and decision-making.

3.3.3 Vulnerability Assessments

An important subset of improved knowledge is information about vulnerability. Identification and synthesis of vulnerabilities will help decision-makers to determine which forest ecosystems, values, and communities are most vulnerable, given the range of likely climate change scenarios. This information can then be used in determining priorities for research and adaptation.

Robust vulnerability assessment tools usable in a range of circumstances are needed. Assessments must be made at scales relevant to the decision-maker and the impact being considered. In the forest sector, the vulnerability of communities has been of particular concern to date, because that is the scale at which the impacts of changing climate may be most immediately evident and at which many on-the-ground adaptation actions will be implemented (Davidson et al. 2003; Parkins and MacKendrick 2007; Williamson et al. 2007). However, at the local scale, vulnerability could also be assessed for parks, ecosystem services, forest managers, and mill managers, whereas on a broader scale companies and provincial and territorial governments also can be vulnerable. Vulnerabilities at any scale may vary considerably, depending on specific circumstances and the adaptive capacity of the participants in the forest sector.

3.3.4 Planning Frameworks and Tools

The forest sector needs a way to integrate and use the best available knowledge for planning and making choices about options for adaptation. Here again, scale is important: frameworks and tools need to be developed and provided at scales relevant to decision-makers. Viable options, including costs and uncertainties, will need to be identified that can address the objectives of the range of sector participants. These objectives might include maintaining habitat and biodiversity, assisting with forest regeneration, optimizing forest products, or managing the sector to optimize mitigation of climate change. Thus, the list of useful tools and techniques is large. Examples include operational-level tools, such as climate-based models of forest growth and yield, seed use and transfer rules and models, and climate-based indicators to inform best practices (e.g., for optimal scheduling of planting and harvesting operations, including salvage); techniques for understanding and incorporating uncertainties and risk into ongoing forest sector decision-making (e.g., by fostering adaptive management); and frameworks for understanding how current forest policies, regulations, and practices could change to increase the flexibility of responses, without compromising future responses.

3.3.5 Coordination and Cooperation

All of the above needs will be met most efficiently through coordination and cooperation. These require improved mechanisms for communicating, working together, and sharing information, knowledge, and experience.

4. CONCLUSIONS

The second section of this report highlighted some of the uncertainties in our understanding of the future impacts of climate change, especially in looking forward to the end of the century, and the third section identified substantial needs related to adaptation. These include the need for greater awareness and debate, better information on vulnerability, improved planning frameworks and tools, and enhanced coordination and cooperation. All participants in the sector need to focus their attention on adaptation; uncertainties, lack of complete information and tools, and the need for potentially contentious debate about adaptation and forest management objectives should not be used as reasons to delay. This focus is urgently needed to minimize the negative impacts of climate change and benefit from any new opportunities that emerge.

Each group of forest sector participants will have specific roles and responsibilities in addressing the challenge of adaptation, although some responsibilities, such as adaptation mainstreaming, need to be shared by all, and coordination and cooperation will improve the overall response. Governments can probably do the most to foster coordination, sharing of knowledge and experience, development of multistakeholder partnerships in planning for adaptation, and promotion of public awareness and debate. In the area of improving knowledge, governments have a long history of supporting research on forests and the factors that influence forest health and the forest sector. They are also well placed to undertake long-term monitoring, synthesis, and timely reporting of climate-related

changes and disturbances in Canada's forests at the local to national level and to support development of tools and frameworks (e.g., the framework to assess the vulnerability of forest-based communities developed by Williamson et al. [2007]). Provincial and territorial governments may be the best placed to support operationally oriented research and development, such as genetic provenance or other species trials, or analysis of the impacts of climate change on growth and yield, in collaboration with industry, universities, and federal scientists. They also can contribute to assessing community needs and vulnerability, together with the communities themselves. On-going collaborative university research in all areas will be important.

The forest-products industry faces the substantial challenge of renewing itself in the face of some of the worst competitiveness conditions it has ever faced. However, its longer term health also depends on how both the domestic and global forests are affected by climate change and by adaptation responses, so it too has an important role to play. For example, it can contribute to operationally oriented research such as trials to assess the effectiveness of site-specific alternative forest practices for adaptation. It can also advise on what types of flexibilities in policies and practices could help in strengthening adaptive capacity.

Meeting the challenge of adaptation will require sustained effort for many years. The relatively small changes in climate in recent decades have already had an appreciable impact on the forest. If the greenhouse gas emission scenarios used in this report occur, then very substantial further impacts will be experienced, as explained in section 2. Although large uncertainties exist concerning the nature, location, and exact scale of the impacts, there is no doubt that the impacts will occur. Even if global efforts to substantially reduce emissions in coming decades are successful, they will not prevent some degree of continuing climate change (for example, increased temperatures, longer growing seasons, and higher risk of drought). In such a case the climate changes would be less severe than projected here, but there would still be impacts on the forest and the forest sector, and adaptation would still be required.

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APPENDIX 1

TERRESTRIAL ECOZONES OF CANADA

Appendix 1. **Terrestrial ecozones of Canada.** Source: Ecological Stratification Working Group. 1996. A national ecological framework for Canada. Agric. Agri-Food Can. Res. Branch, Cent. Land Biol. Resour. Res., Environ. Can., State Environ. Dir., Ottawa, ON. 125 p. Reprinted with permission.

APPENDIX 2

CLIMATE TREND INFORMATION

To examine current climate trends we made use of spatial models described by McKenney et al. (2006a). Climate station data (minimum temperature, maximum temperature, and precipitation) were obtained from Canadian and US sources for the period 1901–2003. Models were generated using ANUSPLIN (Hutchinson 2004), which employs multidimensional thin-plate smoothing splines (a nonparametric curve fitting technique) to develop spatially continuous climate models (i.e., maps), the problem being that climate is recorded at relatively few, scattered locations around the country but reliable estimates are required across entire landscapes. For the present purpose these models were resolved to produce estimates on a regular grid at approximately a 10-km resolution. From the primary climate variables, a further 29 annual bioclimatic indices (Table A2.1) were generated using ANUCLIM (Houlder et al. 2000) and SEEDGROW (Mackey et al. 1996). The climate variables of interest were overlaid with provincial and ecozone maps and mean values were calculated for each combination of province and ecozone. Only a select number of variables were chosen for display in this report, as space is limited.

Historical trends for a climate variable of interest were based on a linear regression between year and the variable for the period 1950–2003. Data from this time period were used because of the scarcity of data before 1950 in much of Canada, particularly for northern ecozones. An autoregressive model was used to correct for serial correlation in the error term (SAS Institute Inc. 2000). The order of the autoregressive model used for each climate variable was determined using backward elimination starting with a 12th order autoregressive model. We urge some caution in the interpretation of these trends because not all the station data used to generate the surfaces have been calibrated to ensure high temporal consistency as is the case in trend studies that are based on individual station records (e.g., Vincent and Mekis 2006). However, there is an important trade-off between the number of stations and the robustness of spatial models: a greater number of stations generally results in better spatial models even though there may be problems with some station data that have not been as thoroughly checked (e.g., location coordinate errors and recording errors).

Table A2.1. Variables derived from primary climate surfaces. Variables 1–19 are generated by ANUCLIM (Houlder et al. 2000); 20–29 are by SEEDGROW (Mackey et al. 1996).

	Variable	Description
1	Annual mean temperature	Arithmetic average (AA) of mean monthly temperatures
2	Mean diurnal range	AA of monthly temperature ranges
3	Isothermality	#2 ÷ #7
4	Temperature seasonality	Standard deviation of monthly mean temperature estimates expressed as a percentage of their mean
5	Maximum temperature of warmest period	The highest monthly maximum temperature
6	Minimum temperature of coldest period	The lowest monthly minimum temperature
7	Temperature annual range	#5 – #6
8	Mean temperature of wettest quarter	AA temperature of 3 wettest months
9	Mean temperature of driest quarter	AA temperature of 3 driest months
10	Mean temperature of warmest quarter	AA temperature of 3 warmest months
11	Mean temperature of coldest quarter	AA temperature of 3 coldest months
12	Annual precipitation	Sum of monthly precipitation values
13	Precipitation of wettest period	Precipitation of the wettest month
14	Precipitation of driest period	Precipitation of the driest month
15	Precipitation seasonality	Standard deviation of the monthly precipitation estimates expressed as a percent of their mean
16	Precipitation of wettest quarter	Total precipitation of 3 wettest months
17	Precipitation of driest quarter	Total precipitation of 3 driest months
18	Precipitation of warmest quarter	Total precipitation of 3 warmest months
19	Precipitation of coldest quarter	Total precipitation of 3 coldest months
20	Start of growing season	Julian date when the mean daily temperature is greater than or equal to 5 °C for 5 days in a row
21	End of growing season	Julian date after August 1st when the minimum temperature reaches <–2 °C
22	Growing season length	#21 – #20
23	Total precipitation for period 1	Total precipitation over the 3 months prior to the start of the growing season
24	Total precipitation for period 3	Total precipitation during the growing season
25	Growing degree-days for period 3	Average daily temperature (°C) minus 5 °C; summed over each day of the growing season
26	Annual minimum temperature	AA of monthly minimum temperatures
27	Annual maximum temperature	AA of monthly maximum temperatures
28	Mean temperature for period 3	AA of temperatures over the growing period
29	Temperature range for period 3	Highest minus lowest temperature during the growing period

Note: Information for variables 1, 5, 6, 12, and 25 is provided in this report.