CLIMATE CHANGE IMPACTS AND ADAPTATION STRATEGIES FOR THE FOREST SECTOR IN CANADA

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Abstract

Impacts on forests will vary regionally across Canada, with continental interior locations likely to experience greater extremes in temperature and precipitation. At the species level there will be short-term physiological responses to climate variability and long-term genetic responses to future climate change. Trees that are adapted to the climate at the time of establishment may be considerably maladapted to the climate at harvest time, displaying reduced productivity and increased frequency of pest attack. Although our ability to pro-actively mitigate possible short-term impacts to current climate change is limited, we have the opportunity to assist species and populations with migration to climatically-suitable habitats. This is a management activity called "assisted migration", and represents an important forest management activity to mitigate the negative consequences of climate change. Other possible management interventions to assist the adaptation of tree species include; improved tree breeding, altered silviculture activities, shorter rotation periods, use of exotics and fast-growing species.

1. Introduction

The diversity of responses to past climate observed in the fossil record can be explained by the diversity of ecological niches represented by tree species, together with the complex and multivariate nature of climate change [1]. Current and future climate change and climate variability are expected to result in small and large-scale responses to species and ecosystems with no modern analogs. Furthermore, the future distribution of genotypes will not only be affected by adaptation to climate change but by competition between and within species [2]. This will create a number of opportunities and challenges for the Canadian forest sector. Under rapid climate change, the relatively slow-growing forests of Canada will be exposed to substantial changes in temperature and/or precipitation over their lifetime. In addition, important natural disturbance processes such as pest and disease outbreaks and fire occurrences will be affected, and will in turn alter forest composition, structure and health. Our ability to sustainably manage forests in Canada is being challenged by climate change, and will require considerable resources directed towards not only understanding the impacts but also how we can respond in a pro-active manner.

In response to the challenge of climate change, the Canadian Council of Forest Ministers recently established a national study of forest sector adaptation. The study has been planned using a phased approach that will assess the consequences of climate change and variability on the physical, biological and socio-economic systems that make up the Canadian forest sector.

The study includes: an assessment of the vulnerability of major commercial tree species in Canada to climate change; identifying expected impacts of climate change on forest ecosystems across Canada; and an assessment of the vulnerability of human systems to changes in forest ecosystem services and values. In this paper we report on the results of the first phase, the assessment of vulnerability at the species level.

2. Climate Trends and Projections for Canada

The recent Canadian National Climate Change Assessment [3] summarizes observed climatic change since the 1950s as follows:

- fewer extreme cold days and nights,
- fewer frost days,
- more extreme warm days and nights,
- decrease in mean amount of daily precipitation,
- decrease in maximum number of consecutive dry days,
- decrease in annual total snowfall (southern Canada), and
- increase in annual total snowfall (northern and northeastern Canada)

The National Assessment also discusses projected future changes across the country. All of Canada, with the possible exception of the Atlantic offshore area, is projected to warm during the next 80 years, although amounts of warming will not be uniform across the country.
On a seasonal basis, warming is expected to be greatest during the winter months, due in part to the feedback effect that reduced snow and ice cover has on land-surface albedo. Rates of warming will be lower in the summer and fall, and summer warming is projected to be more uniform across the country.

Winter warming will likely have a number of impacts on Canadian forests. For example, several forest insect pests are limited by cold winter temperatures which reduce the rates of reproduction. Warmer winter temperatures will likely contribute to increased populations of some of these insects, although other factors such as tree age and forest composition are also important.

Annual total precipitation is projected to increase across the country during the current century. By the 2080s, projected precipitation increases range from 0 to 10% in the far south up to 40 to 50% in the high Arctic. Due to enhanced evapo-transpiration, driven by higher temperatures, many regions will experience a moisture deficit despite greater amounts of precipitation. Of particular concern is the southern edge of the boreal forest in the western provinces. Research has shown that this is a moisture-limited boundary [4]. If precipitation changes only slightly but evapo-transpiration increases substantially due to higher temperatures, moisture deficits will increase in length and severity, potentially causing the loss of forest cover in this region. The recent drought in 2001-2003 resulted in wide spread dieback of aspen in this region and may be an indication of more severe impacts to come [4].

3. Local Adaptation, Autonomous and Assisted Migration

Under climate change tree species will either migrate to track ecological niches spatially; adapt to new conditions in their current location, or become extinct [5]. The extent to which populations will adapt will depend on phenotypic variation, strength of selection, fecundity, interspecific competition, and biotic interactions [5]. For example, species that are restricted to a narrow range of landscape conditions (i.e. "specialists") may fare less well than "generalists" that occupy a wider variety of locations. Migratory success of species will depend on both climatic and non-climatic factors. Non-climatic factors affecting migration include: available seed sources, seed dispersal requirements and opportunities, soil conditions, biotic interactions, age to sexual maturity, fecundity and degree of range fragmentation [5][6][7].

3.1 Species Range Shifts

Climate determines forest types at the global scale and controls species distribution within a region [8]. Under climate change the geographic ranges of many species are moving toward the poles or to higher altitudes in response to shifts in the habitats to which these species have adapted [9]. Some species will be unable to keep up with the movement of their ideal climatic envelope and will face the risk of extinction. However, our ability to predict the response of individual species and ecosystems to climate change is limited. There is no general theory that describes climate-driven responses among disparate tree species due in part to the diversity of ecological niches and growth strategies found among co-occurring species [10].

Williamson et al. [11] summarizes key concerns and observations of species distribution under future climate change;

- The rate of movement in species climatic envelopes will considerably exceed the ability of individual species to migrate;
- New species may be favored at a particular site, but current species have the advantage of site occupation so there may be lags between a change in local climate and change in species composition;
- The range of species that are adapted to hot and dry climates will expand into areas that are currently occupied by species more suited to cooler and moister climates;

McKenney et al. [12] determined the climatic tolerances (the "climate envelope") for 130 North American tree species and mapped the re-distribution of the species under future climate scenarios. They found that, under a scenario in which species were able to fully occupy their future climatic niche, species' ranges decreased in area by an average of 12% and shifted northward an average of 700 km. Under a scenario in which dispersal into new areas was extremely limited, species' ranges decreased by 58% and shifted northward an average of 330 km. Due to large-scale land use change and the built environment, species' ability to disperse to new habitats may be extremely limited in some areas and natural migration unable to keep pace with the shifting climate.

3.2 Management Options

If forest managers are to continue the sustained flow of ecosystem services and maintain important societal values of forests, some human intervention will need to take place. Most likely, changes to reforestation activities will be the primary avenue to enhance resistance, resilience and adaptive potential of individual species and ecosystems [13].

3.2.1 Assisted Migration of Populations

One of the primary manifestations of climate change in forests is expected to be maladaptation – a reduction in productivity, poor stem form and wood quality, and increased susceptibility to pests and disease. Maladaptation is expected to arise because trees' annual growth cycle will become increasingly unsynchronized with the annual climate cycles in which trees evolved and for which they are genetically programmed. Additionally, trees may find themselves in climates suitable to pests to which they have had infrequent exposure and for which they have little resistance. Therefore, establishing plantations with populations of forest trees adapted to future climates (i.e., assisted migration) has been posed as a key climate change adaptation strategy because it addresses the fundamental issue of the uncoupling of plant adaptation to its environment [14][15]. Proactive intervention through assisted migration of seed during plantation establishment should help maintain optimum forest health and productivity [16] [17].

3.2.2 Assisted Migration of Species

There is good evidence that species migration will also lag behind climate migration [5][14][18][19]. As with assisted migration of populations, the climate distance species are migrated will have to be small enough to allow for good survival at establishment, but large enough to ensure good adaptation toward the end of the rotation when growth is maximum. Consequently, assisting the migration of species (also called assisted colonization) has been proposed as an important climate change adaptation strategy. Several modeling approaches have been developed to predict the migration of species' climate niches (see McKenney et al. [12] for a review).

While few people object to moving seed sources within a species' current geographic range (assuming seed transfer guidelines are not violated), moving species into new areas is more contentious because of the potential disturbance to native flora and fauna. MacLachlan et al. [20] point out that the practice is in fact already occurring and encourage politicians, policymakers, and the general public to focus on the risks and uncertainty involved in such movements. Hunter [21] suggests that work needs to be done to identify species and sites that are the most suitable candidates for assisted colonization. The further development of protocols for species movement will invite policy makers to weigh the risks of migrating species outside of their current distributions [9].

3.2.3 Seed Transfer Control

To ensure that plantations being established today will be adapted to future climates, it is first necessary to ensure that systems of seed transfer control (also called seed *procurement* or seed *transfer* guidelines) are in place throughout Canada. Effective implementation of assisted migration of seed lots (see next section) can occur only if a system of seed transfer control is in place. Further, incorporation of assisted migration will be most effective in seed transfer systems that are based on climate. We estimate that approximately half of Canadian jurisdictions currently employ some form of seed transfer control. The B.C. Ministry of Forests and Range Resources recently updated their seed transfer standards to increase elevation limits for seed transfer by 100 to 200 m in order to anticipate the effects of warming in mountainous environments. These new standards will go into effect on April 1st, 2009 [22].

3.2.4 Provenance Tests

The best data to address the question of climate change impacts on population productivity, and to develop response strategies such as assisted migration and increased adaptive diversity, comes from response functions developed from long-term provenance data. In these functions, populations are tested across a wide array of climates, and their performance is related to the test site climate. Numerous provenance tests exist across Canada; however, most were established in the 70s and 80s, for purposes other than climate change investigation, and therefore lack sufficient sampling of populations and site climates. Consequently, there is a dearth of provenance data - even for Canada's primary commercial species - with which to address these crucial issues. An important exception to this is a comprehensive set of provenance tests established in British Columbia for lodgepole pine. These data have been used to develop transfer functions that indicate which seed sources may perform best for a given location under future climate scenarios [17].

A comprehensive series of long-term provenance field tests including seed sources from the northern USA is recommended, as these may become of significant value to Canada as the climate changes. The tests should include the primary forest tree species in Canada. Seed sources of each species should be tested across a wide range of climates, including in climates currently located in neighbouring states.

4. Plant Diseases

One of the least understood aspects of natural disturbance agents in forests are plant diseases. This is due to their complex and often inter-dependent relationships among other disturbance agents, host species availability and condition, stand health and environmental conditions. It is known that climate change will directly affect the pathogen, the host, and the interaction between them [23]. However, understanding exactly how forest diseases will be affected by climate change is extremely challenging, and is further complicated by our lack of knowledge, data and monitoring of forest diseases in Canada.

In a recent review of the impacts of climate change on forests and forest management in Canada, Johnston et al. [24] estimate the loss of annual timber from forest diseases in Canada to be 36 million cubic meters, which translates to one-third of the total annual harvest [25]. Forest diseases in Canada include stem diseases, heartwood rots, stem decay, shoot blights and cankers, foliar and root diseases, mistletoes, viruses and virus-like disorders, vascular wilts, and seed and seedling diseases. The incidence and severity of diseases will change due to anticipated global warming, which will affect the timber sources in the future [26].

Recently a literature review of forest diseases of western North America under climate change was published by the US Forest Service [27]. The authors acknowledge that there is considerable uncertainty about how forest pathogens will respond to climate change, but provided some general observations of expected responses, including:

- Changes will occur in the type, amount and relative importance of pathogens and diseases. With warming, some diseases may be able to occur further north or at higher elevations than under current conditions;
- The epidemiology of plant diseases will be altered. Prediction of disease outbreaks will be more difficult in periods of rapidly changing climate and unstable weather;
- In a rapidly changing environment, host resistance to pathogens may be overcome more rapidly due to accelerated pathogen evolution;
- Interactions between biotic and abiotic diseases may represent the most important effects of climate change on plant diseases;

Johnston et al. [24] indicate that trees become more susceptible to diseases if they are not physiologically adapted to the site. Plants normally defend themselves against disease attack by producing phenolics and tannins. If the host is sufficiently stressed and weakened it may not have enough reserves to produce chemical defences [28]. Drought conditions can create positive environments for pathogens and may also reduce the number and diversity of soil microbes, reducing the availability of plant nutrients required for plant growth [26] [29].

Changes in climate may result in pathogen expansions and declines in the host habitat range, or the host may be released from disease control by changes in environmental conditions [30]. Indirect factors related to climate change can also enhance the resilience of forest ecosystems. Resistance to disease may take the form of increased thickness of the surface wax layer on leaves resulting in increase resistance to fungi that penetrate the tree or plants leaves. Mcelrone et al. [31] proposed that elevated CO_2 altered the leaf chemistry, reduced the stomatal opening, and increased the total phenolics by 15% and tannins by 14%. Increases in atmospheric levels may increase the number of soil microbes resulting in an increase in nutrient availability to plants in areas where water is available [26].

Venier et al. [32] projected the occurrence and distribution of *Sclerodermis* canker disease using historical records of both disease distribution and climate data. These researchers developed a consistent and highly accurate predictive model from the relationship between *Sclerodermis* occurrence and climate. This type of model could be used as a risk assessment tool for large areas to project the occurrence of this disease.

4.1 Plant Disease Management

It is difficult to generalize about the effects of climate change on forests and forest pathogens since the effects will tend to be different for different pathosystems in different locations

[27][33]. Although we know that individual pathogens require different environmental conditions to be successful, and we know these specific conditions for many species, we don't know how host-pathogen interactions will be altered by climate change [27]. These realities post a significant challenge to the management of plant diseases under climate change. Most likely there will need to be adjustments made to current management practices. Garrett et al. [34] describe some of the primary issues to be considered:

- Strategies such as delaying planting to avoid a pathogen may become less reliable;
- For many invasive pathogens, models of climatic conditions and requirements need to be supplemented by information about the availability of susceptible hosts and the likelihoods of transport of pathogens by trade and other human networks;

5. Insects

As trees become increasingly stressed by climate change, existing pest populations and the prevalence of non-native invasive pest species may increase. However, neither the rate nor the geographical scale of anticipated pest response is known [35].

Important pests such as spruce budworm, jack pine budworm and forest tent caterpillar are expected to increase due to the direct effects of increased temperature on reproduction, and the increased susceptibility of host trees due to other stresses, e.g. drought [24][36][37]. The long-term effect of insect outbreaks on forest management is difficult to predict, but recent research provides examples of tree mortality resulting from the interaction of insects, drought and fire in the southern margin of the boreal forest in the prairie provinces [24][36][37][38].

An interesting case study of the interaction between climate, host trees and reproduction is the mountain pine beetle (MPB) in British Columbia. Carroll et al. [39] give the following overview. The MPB is currently in a major outbreak phase in central B.C., affecting some 8.5 million ha primarily in lodgepole pine stands. The insect's distribution is determined by the position of the -40 °C isotherm, which currently limits the beetle's eastward spread to the BC-AB border. However, individuals of this species have been found in shelterbelts up to 300 km east of Calgary, so its ability to spread has been established. If the location of the -40 °C isotherm shifts eastward and northward due to warming, the beetle will likely spread. Lodgepole pine and jack pine interbreed in north-central Alberta, so if the beetle spreads that far east, it may switch hosts from lodgepole to jack pine. Jack pine is closely related to lodgepole pine and has been shown experimentally to be an acceptable host for the beetle. Since the distribution of jack pine extends continuously from Alberta to New Brunswick, an emerging scenario is that of mountain pine beetle spreading from the west coast to the east coast in the next few decades. This would have enormous financial impacts since jack pine is an important commercial species in central and eastern Canada [24].

5.1 Pest Management

The challenges facing forest managers dealing with insects and disease under climate change are similar. Both disturbances types are in need of a major infusion of resources and improved monitoring if forest managers are going to have any impact on managing their establishment and impact on forest resources.

Process-based simulation models have been developed which are based on the physiological response of the pest organism to weather events and climate patterns. Knowledge of pest phenology can be used to build simulation models that explore the effect of changes in temperature, precipitation and other climate variables on pest outbreaks. These models have not yet successfully or comprehensively included all of the other fundamental population processes (e.g. reproduction, dispersal, survival), and thus are limited in their ability to forecast insect outbreaks [35].

Given the lack of detailed understanding of climate change impacts on forest insects and disease, a general strategy is to understand and adhere to the principles of Sustainable Forest Management. These principles have been established by the Canadian Council of Forest Ministers [40] and deal with maintaining forest ecosystem biodiversity, health and productivity. To the extent that these principles are used in forest management, Canadian forest managers will be in the best position to cope with future climate change.

6. Plant Physiology and Productivity

Climate is a major environmental factor affecting the establishment and growth of trees. Changes in climate will produce change in average microclimate, with consequent impacts on the physiological processes of photosynthesis and plant respiration and effects on regeneration success, species survival, and primary production [11][26][42]. Physiological responses of plants to current climate change are already occurring in Canada. Bernier and Houle [43] noted that sugar maple bud-burst is occurring several days earlier than it did a hundred years ago and Colombo et al. [26] report similar results for white spruce in Ontario. Beaubien and Freeland [44] report that flowering for aspen is now occurring 26 days earlier than it did in the last century. It is expected that the change and impacts that are currently being observed may be precursors of even more significant events in the future as our climate continues to warm at a potentially even more rapid rate.

Recent research suggests that forest productivity may decline on site conditions that are currently marginal with regard to water and nutrient availability [11][37]. On the other hand, sites that are not limited by these factors may experience increased growth due to the effects of CO_2 fertilization and increased water use efficiency. Managers may need to begin considering how their investments of time and resources can best be directed to locations where the chances of increased future growth are the highest [11][24].

Our ability to mitigate the negative short-term consequences of climate change and climate variability on plant physiology is limited. However, an understanding of physiological responses of individual species to climate change will enable us to make more informed decisions about seed and planting site selection, as well as improve the methodology behind growth and yield estimations.

7. Conclusions

Climate change will likely have major effects on Canada's forests, although these will vary substantially in nature and severity across the country. The first phase of the CCFM forest sector vulnerability study is focused on species-level impacts and adaptation options. We find that there is a great deal known for a few commercially important species but relatively little known for many others. Assisted migration will probably be an important management response to species-level impacts, increasing the likelihood that future populations are established in locations in which the future climate will be suitable. With the exception of BC, few jurisdictions have begun to address this option through policy change although some are considering it.

Impacts of climate change related to insects and disease is only just beginning to be addressed and the knowledge gaps are large. Development of more sophisticated modelling capacity will help, although lack of data on many pests and diseases is a constraint. In the absence of detailed data, application of the well-understood principles of Sustainable Forest Management will assist forest managers in maintaining forest ecosystem health and productivity to the extent possible.

The effects of climate change on tree physiology and productivity can't be managed directly. However, a better understanding of these processes can allow forest managers to better match tree species with site conditions and take advantage of locations where the impacts of climate change may be neutral or positive.

8. References

[1] Jackson S., "Impacts of past climate change on species distribution of woody plants in North America", Climate Change and Forest Genetics: 29th Canadian Tree Improvement Association Meeting, July 26-29 2004, pp.4-2.

[2] Rehfeldt G., "Biome, species, and population responses to climate and to climate-change in Siberia and western North America", Climate Change and Forest Genetics: 29th Canadian Tree Improvement Association Meeting, July 26-29 2004, pp.4-5.

[3] Lemmen D.S., Warren F.J., Lacroix J., and Bush E., editors, "From impacts to adaptation: Canada in a changing climate 2007", *Government of Canada*, 2008.

[4] Hogg E.H., Brandt J.P., and Michaelian M., "Impacts of a regional drought on the productivity, dieback and biomass of western Canadian aspen forests", *Canadian Journal of Forest Research*, Vol. 38, 2008, pp.1373-1384.

[5] Aitken S.N., Yeaman S., Holliday J.A., Wang T., and Curtis-McLane S., "Adaptation, migration or extirpation: climate change outcomes for tree populations", *Evolutionary Applications*, Vol. 1, Iss. 1, 2008, pp. 95-111.

[6] Pearson R.G., and Dawson T.P., "Predicting the impacts of climate change on the distribution of species: are bioclimate envelope models useful?", *Global Ecology and Biogeography*, Vol. 12, 2003, pp. 361-371.

[7] Guisan A., and Thuiller W., "Predicting species distribution: offering more than simple habitat models", *Ecology Letters*, Vol. 8, 2005, pp.993-1009.

[8] Wang T., Aitken S., O'Neill G., Yanchuk A., Spittlehouse D., Campbell E., and Hamann A., "Use of genetic variation in forest trees to adapt to changing climate", 2008, Powerpoint presentation accessed online http://www.for.gov.bc.ca/ftp/HTI/external/!publish/Climate%20Change/Seminar_Series/Archive/Nov_13_08_wang_etal_short.pdf.

[9] Hoegh-Guldberg O., Hughes L., McIntryre S., Lindemayer B., Parmesan C., Possingham H.P., and Thomas C.D., "Assisted Colonization and Rapid Climate Change", *Ecology*, Vol. 321, 2008, pp.345-346.

[10] Green S., "Climate-change response strategies among three co-occurring, ecologically distinct northern coniferous tree species", *Climate Change and Forest Genetics: 29th Canadian Tree Improvement Association Meeting*, July 26-29 2004, pp.4-10.

[11] Williamson T., Colombo S. Duinker P., Gray P., Hennessey R., Houle D., Johnston M., Ogden A., and Spittlehouse D., "Climate change and Canada's forests: current and predicted impacts", Sustainable Forest Management Network, Edmonton, AB, [In press].

[12] McKenney D., Pedlar J., Lawrence K., Campbell K., and Hutchinson M., "Potential impacts of climate change on the distribution of North American trees", *BioScience*, Vol. 57, 2007, pp. 939-948.

[13] Barber B. "Reforestation strategies for adapting British Columbia's managed forests to climate change: policy barriers and opportunities", Masters Thesis, University of British Columbia, 1987, p. 102.

[14] Rehfeldt G.E., Crookston N.L., Warwell M.V., and Evans J.S., "Empirical analyses of plant–climate relationships for western United States", *International Journal of Plant Science*, Vol. 167, 2006, pp. 1123-1150.

[15] Millar C.I., Stephenson N.L., and Stephens S.L., "Climate change and forests of the future: managing in the face of uncertainty", *Ecological Applications*, Vol. 17, 2007, pp. 2145-2151.

[16] Rehfeldt G.E., Ying C.C., Spittlehouse D.L., and Hamilton D.A. Jr., "Genetic responses to climate in Pinus contorta: niche breadth, climate change, and reforestation", *Ecological Monographs*, Vol. 69, 1999, pp. 375-407.

[17] Wang T., Hamann A., Yanchuk A., O'Neill G.A., and Aitken S.N., "Use of response functions in selecting lodgepole pine populations for future climates", *Ecological Monographs*, Vol. 12, 2006b, pp. 2404-2416.

[18] Iverson L.R., and Prasad A.M., "Potential redistribution of tree species habitat under five climate change scenarios in the eastern US", *Forest Ecology and Management*, Vol. 155, 2002, pp. 205-222.

[19] Hamann A., and Wang T., "Potential effects of climate change on ecosystem and tree species distribution in British Columbia", *Ecology*, Vol. 87, 2006, pp. 2773-2786.

[20] McLachlan J.S., Hellmann J.J., and Schwartz M.W., "A framework for debate of assisted migration in an era of climate change", *Conservation Biology*, Vol. 21, 2007, pp. 297–302.

[21] Hunter M.L., "Climate change and moving species: furthering the debate on assisted colonization", *Conservation Biology*, Vol. 21, No. 5, 2007, pp. 1356–1358.

[22] BCMoFR (British Columbia Ministry of Forests and Range). 2008c. Chief Forester's Standards for Seed Use, Amendments to the Standards – November 2008. BCMoFR, Victoria, BC. Also available on-line: http://www.for.gov.bc.ca/code/cfstandards/amendmentNov08.htm, accessed 17 December 2008.

[23] Brasier C., "Climate change and tree health", *Proceedings, Trees in a Changing Climate conference, University of Surrey in Guilford, June 2005.* Online: http://www.rhs.org.uk/research/climate_change/documents/tiaccBrasierSum.pdf

[24] Johnston M., Williamson, T, Price D., Spittlehouse D., Wellstead A., Gray P., Scott D., Askew S, and Webber, S., "Adapting forest management to the impacts of climate change in Canada", Final Report, Research Integration Program, BIOCAP Canada. Available at http://www.biocap.ca/rif/report/Johnston_M.pdf.

[25] Hepting, G. N, V. J. Nordin, T. S. Buchanan, R. R. Lejeune, G. P. Thomas, C. W. Farstad, H. Pschorn-Walcher, J. E. Kuntz, F. Roll-Hansen and J. S. Murray, with assistance by B. M. McGugan and B. Lekander., "The importance of forest diseases and insects.", Food and Agriculture Organization of the United Nations (FAO/IUFRO) Document Respository Unasylva No 78. http://www.fao.org/documents/show_cdr.asp?url_file=/docrep/24847e/24847e08.htm. Accessed online: December 17, 2008.

[26] Colombo S.J., Cherry M.L., Graham C., Greifenhagen S., McAlpine R.S., Papadopol C.S., Parker W.C., Scarr R., Ter-Mikaelian M.T., and Flannigan M., "The impacts of climate change on Ontario's forests", Ontario Forest Research Institute (OFRI), S.J. Columbo and L.J. Buse (eds.), Forest Research Information Paper No. 143, 1998, p. 56.

[27] Kliejunas J.T., Beils B., Micales-Glaeser J, Michaels-Goheen E., Hennon P., Mee-Sook H., Kope H., Stone J., Sturrock R., Frankel S., "Climate and forest diseases of western North America: a literature review [Final Draft]", United States Department of Agriculture Forest Service, 2008, p. 36.

[28] Horsley S.B., Long R.P., Bailey S.W., Hallett R.A., and Wargo P.M., "Health of eastern North American sugar maple forests and factors affecting decline", *Northern Journal of Applied Forestry*, Vol. 19. p. 34-4.

[29] Ayres M.P, and Lombardero M.J., "Assessing the consequences of global change for forest disturbance from herbivores and pathogens", *The Science of the Total Environment*, Vol. 262, 2000, pp. 263-286.

[30] Harvell C.D., Mitchell C.E., Ward J.R., Altizer S., Dobson A.P., Ostfeld R.S., and Samuel M.D., Climate warming and disease risks for terrestrial and marine biota, *Science*, Vol. 296, No. 5576, 2002, pp. 2158-2262.

[31] Mcelrone R., Reid A., Hoye C., Hart K., and Jackson R., "Elevated CO2 reduces disease incidences and severity of a red maple fungal pathogen via change in host physiology and leaf chemistry", *Global Change Biology*, Vol. 11, 2005, pp. 1828-1836.

[32] Venier L.A., Hopkin A.A., McKenney D.W., and Wang Y., "A spatial, climatic-determined risk rating for *Scleroderris* disease in Ontario", *Canadian Journal of Forestry Research,* Vol. 28, 1998, pp. 1398-1404.

[33] Sturrock R.N., Climate change effects on forest diseases: an overview. *In: Jackson, M.B. (comp). Proceedings 54th Annual Western International Forest Disease Work Conference*, October 2-6, 20006, Smithers, B.C., p. 51-55.

[34] Garrett K.A., Dendy S.P., Frank E.E., Rouse M.N., and Travers S.E., "Climate change effects on plant disease: genomes to ecosystems", *Annual Review of Phytopathology*, Vol. 44, 2006, pp. 489-509.

[35] Abbott C.L., Bennett K.E., Campbell K., Murdock T.Q., Swain H., "Summary report: forest pests and climate change", Symposium: October 14-15, 2007. Pacific Climate Impacts Consortium, Victoria BC, p. 14.

[36] Hogg E.H., Brandt J.P., and Kochtubajda B., "Growth and dieback of aspen forests in northwestern Alberta, Canada, in relation to climate and insects", *Canadian Journal Forest Research*, Vol. 32, 2002, pp. 823–832.

[37] Hogg E.H., and Bernier P., "Climate change impacts on drought-prone forests in western Canada", *The Forestry Chronicle*, Vol. 81, 2005, pp. 675-682.

[38] Volney W.J.A., and Hirsch K.G., "Disturbing forest disturbances", *The Forestry Chronicle*, Vol. 81, 2005, pp. 662-668.

[39] Carrol, A., Taylor S., Regniere J., and Safranyik L., "Effects of climate change on range expansion by the mountain pine beetle in British Columbia", *In: Proceedings of Mountain Pine Beetle Symposium: Challenges and Solutions, Oct. 30-31, 2003 Kelowna,* BC, T.L. Shore and J.E. Stone (eds). Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre Information Report BC-X-399, 2004, pp. 233-244.

[40] Canadian Council of Forest Ministers, "Defining Sustainable Forest Management in Canada: Criteria and Indicators 2003", Canadian Council of Forest Ministers, Secretariat Office, Canadian Forest Service, Ottawa ON, 2003, 27 pp. Available on-line at: http://www.ccfm.org/pdf/CI_Booklet_e.pdf, accessed 17 December 2008.

[41] Kirschbaum M.U.F., "Forest growth and species distribution in a changing climate", *Tree Physiology*, Vol. 22, No. 5-6, 2000, pp. 309-322.

[42] Bernier P., and Houle, D. Les changements climatiques et la productivité forestière. Pages 13–17 in A.T. Pham (ed.), Actes du colloque changements climatiques et foresterie : impacts et adaptation. Forestry Resources Report, 2005, Ouranos Climate Research Consortium, Montreal, QC.

[43] Beaubien E.G., and Freeland H.J., "Spring phenology trends in Alberta, Canada: links to ocean temperatures", *International Journal of Biometeorology*, Vol. 44, 2000, pp. 53-59.