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CANADIAN FOREST HEALTH GENOMICS

CANADIAN STRENGTHS ADDRESS FORESTRY CHALLENGES

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CONTENTS

Executive Summary	3
Introduction	5
Challenges in Forest Health.....	6
Role of Genomics in Mitigating the Issues	11
Addressing Changing Ecosystems Due to Climate Change	12
Minimizing the Effects of Invasive Pests and Other Organisms	12
Improving Overall Forest Health.....	13
Industrial Use of Damaged Trees.....	13
Understanding and Addressing the Social Context of Forest Genomics	14
The Socioeconomic Promises of Continuing Genomics Research.....	14
Projects Targeting Multiple Pest Species.....	14
The Spruce Budworm: A Model System for Forest Genomics	15
Mitigating the Mountain Pine Beetle Threat	16
Investigating the Emerald Ash Borer	17
Summary of the Socioeconomic Outcomes of Genomics Research.....	17
Success of Past Canadian Investments in Forestry Genomics	19
Canada’s Leadership and Strengths.....	19
World-Class Leadership	19
Forestry Genomics Capacity from the Atlantic to the Pacific	20
Next Steps Toward Success.....	20
Appendix 1. Current and Predicted Regional Forest Health Threats	22
Appendix 2. Current and Past Large-Scale Canadian Genomics Forestry Projects.....	25
Appendix 3. Canada’s Large-Scale Science and Technology Platforms and R&D Centres.....	28
Appendix 4. Forest Health and Biofuel Genomics Expertise in Canada	29

EXECUTIVE SUMMARY

Forestry is one of Canada's major economic engines as well as a socio-cultural icon. However, sustainable access, climate change, and increasing international trade are presenting major challenges to the forest sector, not least of which are threats by native and alien organisms (e.g., insects, fungi). As a response, forest stakeholders see an expanded role for research and innovation to help mitigate the issues. Genomics research is an important part of this innovation strategy. This document outlines the objectives of the Canadian Forest Health Genomics Initiative (CFHGI) to facilitate a greater understanding of forest health issues and identify areas where national collaborative genomics research can have the most socioeconomic and ecological impact.

Threats to the health of Canada's wild and urban forests are increasing rapidly, with almost 5% of the total lost to more than 180 pest insect species in 2006. In addition, climatic shifts are impacting whole forest ecosystems as soil conditions, temperatures, precipitation, spring/fall cycles, and freeze-thaw conditions change. Many plant species will struggle to adapt to the new environmental situation in the 21st century, as the range of native and alien pests expands. Furthermore, destruction by forest pests and climatic shifts are resulting in significant social, economic, and ecological costs across Canada, including lost incomes, reduced land values, cultural impacts, and major shifts in biodiversity and natural ecosystem functioning. They could even result in Canada becoming a net emitter of carbon, rather than a carbon sink.

Hundreds of pest insects and diseases, such as the spruce budworm (SBW), mountain pine beetle (MPB), tent caterpillar, emerald ash borer (EAB), Asian long-horned beetle, brown spruce longhorn beetle, root rot, Dutch elm disease, and sudden oak death are posing current or potential threats to Canada's forests. The participants at the inaugural CFHGI Workshop held March 31, 2009 identified at that time three pests as particularly serious that could be used as models by genome researchers to address global forest health issues: the SBW, MPB (and its associated pathogenic fungi), and EAB. A prolonged infestation with the spruce budworm is severely affecting the pulp and paper, balsam oil, wreath and garland, and other industries, as well as accelerating natural fire cycles from Alberta to the Atlantic. Climatic shifts are also allowing the MPB to significantly increase its range across BC and Alberta and threaten Canada's boreal forests, with potentially devastating economic, community, and ecological impacts. Lastly, the rapidly spreading introduced EAB is currently a major concern for urban forests and natural stands of ash in Ontario and Quebec.

The genome sciences¹ are promising to deliver increasingly affordable new technologies to help meet the challenges facing our forest industry, aid in sector transformation, and integrate with existing forest management tools to ensure a prosperous and sustainable future for Canada's entire forest sector. Genomics unravel molecular interactions at the systems level, helping us to understand the relationship between the tree and the pest, interactions with environmental factors, and pest and disease impacts on the wider forest ecosystem. Genomics research can help identify key genes that confer adaptive traits against pest infestation, disease, or environmental changes; identify genes or genetic features that provide an accurate diagnosis of invading organisms; identify targets for treatment and control of the infestation; monitor for

¹ The genome sciences (also called "genomics" in this document) include: genomics; transcriptomics; proteomics; metabolomics; metagenomics; systems biology; bioinformatics. These different disciplines are described in a footnote in the main body of the text.

invasive pests and diseases; and support risk assessment and regulation. Genomics technologies also offer numerous opportunities to the biofuel industry, which can utilize the damaged trees. Furthermore, the CFHGI will address the social, economic, and environmental risks and benefits of genomics-based solutions for forest health.

By coordinating our efforts nationally, we will address the challenges by capitalizing on Canadian strengths. Canada's forestry genomics researchers are world leaders, particularly in the areas of conifer and forest pest research. Our scientists are involved in many global projects, and participated in the international sequencing of the black cottonwood genome. The federal and provincial governments have built forestry genomics capacity over the past nine years with large investments in projects and internationally competitive technology platforms.

Genomics research has already proven itself in forestry, with the development of several complementary management tools. For example, a kit developed by the Canadian Forest Service (CFS) is being used in Canada and the US to certify that Canadian nurseries are free of the pathogen that causes sudden oak death, thereby allowing Canadian producers to export their materials. CFS researchers also characterized and commercialized (via Sylvar Technologies) a naturally occurring insect virus as a pest management product (Abietiv™) to kill balsam fir sawfly. Furthermore, a modified spruce budworm virus is currently being presented as a test case for the registration of such agents to the Pest Management Regulatory Agency. The CFHGI will build upon and expand the expertise developed in these and other projects, such as those that target the SBW, MPB, and EAB.

INTRODUCTION

Forestry is an important part of Canadian culture as well as a major economic engine. At more than 400 million hectares, Canada contains 10% of the planet's forests, and is one of only three countries in the world still retaining vast areas of virgin, untouched stands. Trees cover almost half of Canada's total landmass and their products account for over 55% of the country's trade balance². In 2007, \$33.6 billion worth of forest products were exported from Canada, making it the largest exporter of forest products internationally, while the industry directly and indirectly employed over 290,000 and 450,000 people, respectively³.

The forest sector is facing an increasing number of challenges, notably a pressing need for sustainable access to forest resources, higher energy costs, and a difficult market for wood products. Furthermore, climate change, increasing international trade, and human activities have made our valuable forests vulnerable to threats by both native and alien organisms, including insects, fungi, and invasive plants, e.g., noxious weeds. According to the International Union for Conservation of Nature (IUCN), invasive alien species (IAS) are the second most significant threat to biodiversity after habitat loss⁴. In Canada, the genetic diversity of at least a dozen highly valuable hardwood species is under threat from IAS damage⁵. Combined with the potentially harmful effects of climate change and increased global consumption of renewable resources, native and alien pests threaten the sustainability of forests in many parts of the country.

As a response to the challenges, stakeholders such as Natural Resources Canada and the Forest Products Association of Canada see an expanded role for research and innovation to help transform the forest sector and enable it to meet growing international demands in an uncertain environment³. For example, intensively managed plantations close to mills would be economically advantageous, as well as beneficial to forest-dependant communities. By using innovative technologies to breed for pest resistant lines, develop environmentally-sound pest control products, and accurately identify and monitor pests for integrated pest management, such plantations could become a reality. They could further advance Canada's forest sector as a world leader of sustainable forest management, and a unique protector of natural global carbon reserves.

The Canadian Forest Health Genomics Initiative (CFHGI) is intended to facilitate a greater understanding of regional and national forest health issues and identify areas where national genomics research can have most impact. This document proposes a rationale for harnessing and directing new interdisciplinary, collaborative genomics research across Canada in those areas with the highest likelihood of positive socioeconomic and ecological outcomes. Its content is guided, in part, by the results of discussions between academic, provincial and federal researchers, policy- and decision-makers, industry, and community groups at a national one-day workshop held on March 31, 2009⁶.

² The State of Canada's Forests 2005- 2006: Forest Industry Competitiveness. Natural Resources Canada. 2007.

³ The State of Canada's Forests Annual Report 2008. Natural Resources Canada. 2008.

⁴ "Species Extinction – The Facts". http://cmsdata.iucn.org/downloads/species_extinction_05_2007.pdf. Accessed May 30, 2009.

⁵ Beardmore, et al. A survey of tree species of concern in Canada: the role for genetic conservation. *The Forestry Chronicle*. 2006 May/June; 82(3). <http://article.pubs.nrc-cnrc.gc.ca/RPAS/rpv?hm=HInit&journal=afc&volume=82&afpf=afc82351-3.pdf>. Accessed June 5, 2009.

⁶ Canadian Forest Health Genomics Initiative Workshop – March 31, 2009. Workshop Report.

CHALLENGES IN FOREST HEALTH

Threats to the health of Canada's wild and urban forests are increasing rapidly. More than 19 million hectares of Canada's forests (or almost 5% of the total) were lost to pest insects alone in 2006³. The most important and destructive of the more than 180 problem species are the native spruce budworm, mountain pine beetle, and tent caterpillar⁷, as well as growing threats from recent arrivals such as the emerald ash borer, Asian long-horned beetle, and brown spruce longhorn beetle⁸. Pathogenic fungi and algae that cause diseases such as root rot, Dutch elm disease⁹, and sudden oak death are also rampant¹⁰. In addition, new pest species are now entering Canada and threaten the future health of our forests. These additional threats include the hemlock woolly adelgid, beech bark disease, and butternut canker, as well as several species of non-native plants. A list of each province's most important forest pest species can be found in Appendix 1.

Climatic shifts are also impacting whole forest ecosystems as soil conditions, ambient temperatures, and precipitation regimes change; and spring/fall cycles oscillate unpredictably. Many plant species will struggle to adapt to the new environmental situation over the next 20 – 90 years¹¹, from both climatic shifts and an expansion of the range of their native and alien pests. Mitigating climate change and adapting to its effects is one of the principal tenets of Natural Resources Canada's vision for the future of the country's forests¹². Long term sustainable forest management practices offer major potential for addressing the broad uncertainties related to climate change¹³, including exacerbated damage from pests.

Destruction by forest pests, as well as climatic shifts, are resulting in significant social, economic, and ecological costs across Canada, including lost incomes, reduced land values, cultural impacts (particularly in rural and aboriginal communities), and major alterations in biodiversity and natural ecosystem functioning. For example, recurrent infestations with the native spruce budworm slow tree growth through repeated defoliation, thus reducing the timber value of the tree at harvest. Defoliation also makes the trees susceptible to other opportunistic organisms that are not usually prevalent in healthy trees. The budworm's major host, the balsam fir, is a major constituent of boreal forests across much of the country. It is also a commercially important species for the production of pulp for paper, as well as for emerging and high profit-margin products such as chemical extracts (balsam oil), plastic-wood composites in the car and construction industries, decorative manufactured goods (wreaths and garlands), and live Christmas trees. During a 15-year outbreak in the 1970s and 1980s, spruce budworm larvae caused devastation in Ontario, Quebec, New Brunswick and Nova Scotia, consuming

⁷ Natural Resources Canada. <http://canadaforests.nrcan.gc.ca/statsprofile>. Accessed May 28, 2009.

⁸ Natural Resources Canada. http://canadaforests.nrcan.gc.ca/article/trend/top_suj/24. Accessed May 28, 2009.

⁹ Vectored by a bark beetle, similar to the spread of a fungus by mountain pine beetle.

¹⁰ An Invasive Alien Species Strategy for Canada. 2004. http://www.ec.gc.ca/eee-ias/98DB3ACF-94FE-4573-AE0F-95133A03C5E9/Final_IAS_Strategic_Plan_smaller_e.pdf. Accessed May 5, 2009.

¹¹ The Importance of Forest Sector Adaptation to Climate Change. Natural Resources Canada (Northern Forestry Centre) 2008. http://nofc.cfs.nrcan.gc.ca/bookstore_pdfs/29154.pdf. Accessed May 27, 2009; Natural Resources Canada Climate Change Posters. http://adaptation.nrcan.gc.ca/posters/index_e.php. Accessed May 27, 2009, e.g., http://adaptation.nrcan.gc.ca/posters/on/on_07_e.php.

¹² Natural Resources Canada. *A Vision for Canada's Forests 2008 and Beyond*. 2008.

¹³ Nabuurs GJ, Masera O, Andrasko, K. et al. Forestry. In *Climate Change 2007: Mitigation*. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, UK and New York, NY, USA. www.ipcc.ch/pdf/assessment-report/ar4/wg3/ar4-wg3-chapter9.pdf. Accessed May 14, 2009.

enough trees to equal a decade's worth of harvest by the eastern forest industry¹⁴. In the drier and warmer conditions predicted under climate change, spruce budworm defoliation could change current forest fire regimes and contribute to greater carbon release from the boreal forest¹⁵.

Climate change has also impacted the range and host expansion of the native mountain pine beetle. Geographical range expansion of this insect in British Columbia (BC) was previously limited by frigid winters. Warmer winters have helped this insect and its associated fungal pathogens to reach unprecedented epidemic proportions in BC and to colonize NW Alberta. The beetles have killed more than 10 million hectares of pine trees in BC, inflicting tens of billions of dollars in damage, and are projected under current climate models to spread over the entire pine dominated sections of the province and further into Alberta by 2013¹⁶. As well as damaging the natural ecological communities in these forests, their effect on the forest industry currently impacts more than 30 BC communities and 25,000 families¹⁷, with additional repercussions on the tourism and recreation industries. Furthermore, destruction by the mountain pine beetle may result in BC's forests switching from a carbon sink to a carbon emitter, thereby adding to, rather than alleviating, global warming¹⁸.

Other native species have also caused economic and ecological problems. The white pine weevil has reduced annual Sitka spruce plantations in BC from more than 10 million to less than 1 million seedlings¹⁹. In eastern Canada, hemlock looper outbreaks are often devastating. The impact of the most recent looper infestation is estimated to have cost between \$248M to \$632M in the province of Quebec alone²⁰.

Among all pests and diseases attacking our forests, invasive alien species are perhaps the most worrisome. The rapidly spreading emerald ash borer attacks and kills all species of ash present in its current range in Canada and is a major concern for urban forests, riparian zones, and natural stands of ash. For example, the city of Oakville has estimated the total replacement costs of its 176,000 ash trees at \$86M²¹.

In addition, the Asian long-horned beetle is considered a potential threat to urban forests, particularly to Canada's iconic sugar maple. Sugar maple is frequently planted in the urban landscapes of eastern Canada and helps to reduce air pollution, absorb storm waters and, in the near future, may contribute to carbon credit trading revenues collected by cities²². The economic impact of this beetle could also significantly affect the sugar maple industry, which has generated between \$190M and \$234M in export revenues annually over the past three

¹⁴ Natural Resources Canada. <http://cfs.nrcan.gc.ca/news/455>; <http://canadaforests.nrcan.gc.ca/articletopic/180>. Accessed May 13, 2009.

¹⁵ Fleming RA, Candau J-N, McAlpine RS. Exploratory Retrospective Analysis of the Interaction Between Spruce Budworm (SBW) and Forest Fire Activity. http://adaptation.nrcan.gc.ca/projdb/pdf/28_e.pdf. Accessed June 9, 2009.

¹⁶ British Columbia's Mountain Pine Beetle Action Plan 2006-2011. Ministry of BC Forests and Range. 2006; The State of Canada's Forests Annual Report 2008. Natural Resources Canada. 2008.

¹⁷ Paul Jay. CBC News. 2008. The Beetle and the Damage Done. cbc.ca/news/background/science/beetle.html. Accessed June 3, 2008.

¹⁸ Kurz WA, et al. Mountain pine beetle and forest carbon feedback to climate change. *Nature*. 2008; 452:987-990. www.nature.com/nature/journal/v452/n7190/full/nature06777.html.

¹⁹ Canadian Forest Health Genomics Initiative Workshop – March 31, 2009. Workshop Report.

²⁰ Natural Resources Canada. <http://cfs.nrcan.gc.ca/news/307>. Accessed June 9, 2009.

²¹ Oakville's Urban Forest. www.oakville.ca/Media_Files/forestry/UFORE.pdf. Accessed June 9, 2009.

²² Federation of Ontario Naturalists. Urban Forests. An Important Part of our Natural Heritage. www.ontarionature.org/pdf/urban_forest.pdf. Accessed June 9, 2009.

years²³. In Nova Scotia, the direct costs of dealing with the brown spruce longhorn beetle are in the tens of millions of dollars. Additional costs related to other values such as recreation, aesthetics, and urban forestry are difficult to assess but nonetheless important. Fumigating or heat treating wood packaging materials from China and Hong Kong to prevent additional imports of these beetle species has become necessary to protect over \$30 billion in trade between Canada and China-Hong Kong²⁴.

Invasive alien species also threaten Canada’s nascent biofuels industry by reducing feedstock. Furthermore, introduced beech bark disease has spread through the Atlantic provinces and into Ontario and Quebec, ravaging 3,500 hectares of forest and affecting 30,250 cubic metres of beech wood with no limits in sight³. All these exotic species seriously threaten the successful shift of Canada’s forest industry towards its new role in a value-added biocomposite economy.

Among the multiple insects and diseases that negatively impact Canada’s forests, the participants at the March 31, 2009 Canadian Forest Health Genomics Initiative Workshop identified at this time three as particularly serious that could be used as models by genomics researchers to address global forest health issues: the spruce budworm, mountain pine beetle, and emerald ash borer. These three impact many aspects of the forest sector across provinces²⁵, as illustrated in Table 1.

Table 1. Direct and Indirect Impact of Three Major Canadian Forestry Pest Insects

	Spruce Budworm	Mountain Pine Beetle	Emerald Ash Borer
Affected and At Risk Provinces:	Atlantic provinces, Quebec, Ontario, Manitoba, Alberta	BC, Alberta <u>At risk:</u> Saskatchewan, rest of boreal forest	Quebec, Ontario <u>At risk:</u> Atlantic provinces, Manitoba
Economic, Social, and Ecological Impacts:	Forest industry	Forest industry	Forest industry
	Feedstock for bioenergy	Feedstock for bioenergy	Feedstock for bioenergy
	Communities, parks, recreational users	Urban forest	Urban forest
	Provincial governments	Provincial governments	Municipal governments & regional conservation authorities
	Carbon trading potential	Carbon trading potential	Carbon trading potential
		Forest-dependent communities	Riparian zones
		Property/land owners	

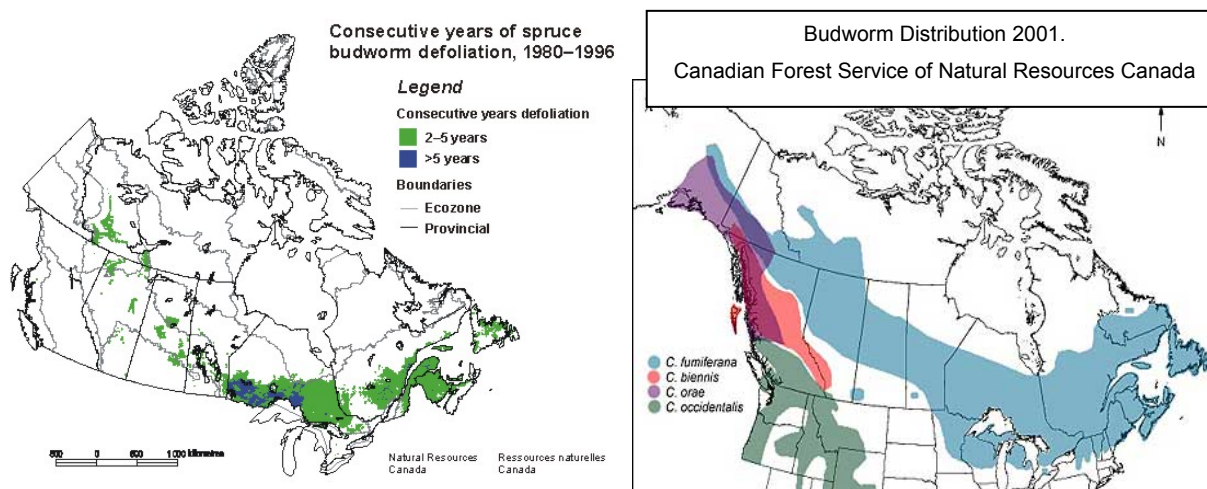
²³ Natural Resources Canada. <http://canadaforests.nrcan.gc.ca/statsprofile/trade/ca>. Accessed May 28, 2009.

²⁴ An Invasive Alien Species Strategy for Canada. Natural Resources Canada. 2004. www.ec.gc.ca/eee-ias/Default.asp?lang=En&n=98DB3ACF-1. Accessed May 5, 2009.

²⁵ The people and organizations that derive value and create wealth and well-being from the forest and its related resources, i.e., governments, municipalities, conservation and environmental groups, woodlot and other land owners, Aboriginals, urban forestry interests, lumber and pulp and paper producers and value-added industries, forest-reliant communities, the recreation and tourism industries, and other sectors of the economy (including the energy, chemical, and pharmaceutical industries). Natural Resources Canada. *A Vision for Canada’s Forests 2008 and Beyond*. 2008.

Figure 1 displays the extent of defoliation by the spruce budworm between 1980 and 1996 and the budworm's distribution in 2001 (the most recent data available)²⁶, while Figure 2 shows the rapid spread of the mountain pine beetle between 1999 and 2007. This area has increased significantly since that time, with 50% of mature pine in BC now dead²⁷. Figure 3 highlights the locations of the emerald ash borer in North America and shows the anticipated rapid spread of the infestation over the next few years²⁸. Under a no-management scenario, this exotic species is expected to spread 18 miles (approximately 30 km) per year. It almost completely destroys all ash species within 3-5 years after infestation²⁹.

Figure 1. Distribution of and Extent of Defoliation by the Spruce Budworm Between 1980 and 1996 and in 2001²⁶ In the illustration for 2001, the distribution of the spruce budworm (*C. fumiferana*) is depicted in blue.



²⁶ Environment Canada. http://ec.gc.ca/soer-ree/English/Indicators/Issues/Forest/Tech_Sup/fosup6_e.cfm?StrPrint=true&. Accessed May 27, 2009; Natural Resources Canada. <http://cfs.nrcan.gc.ca/subsite/budworm>. Accessed June 29, 2009.

²⁷ Canadian Forest Service of Natural Resources Canada.

²⁸ www.doacs.state.fl.us/pi/enpp/ento/agrilus_planipennis.html. Accessed June 25, 2009.

²⁹ Minnesota Dept. of Agriculture. www.mda.state.mn.us/plants/pestmanagement/eabstrategies.htm. Accessed June 26, 2009.

Figure 2. Growth of Area Covered by the Mountain Pine Beetle Outbreak, 1999 to 2007²⁷

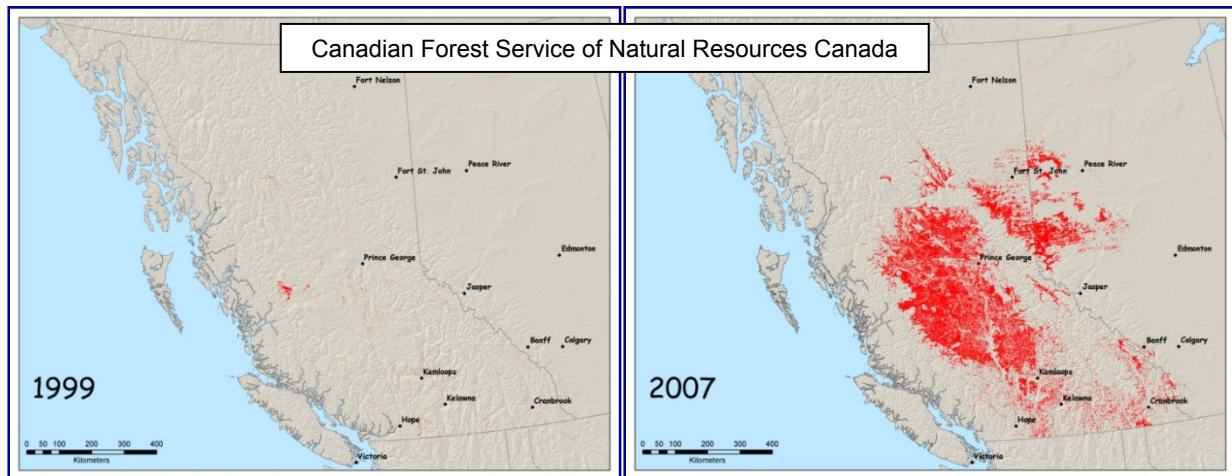
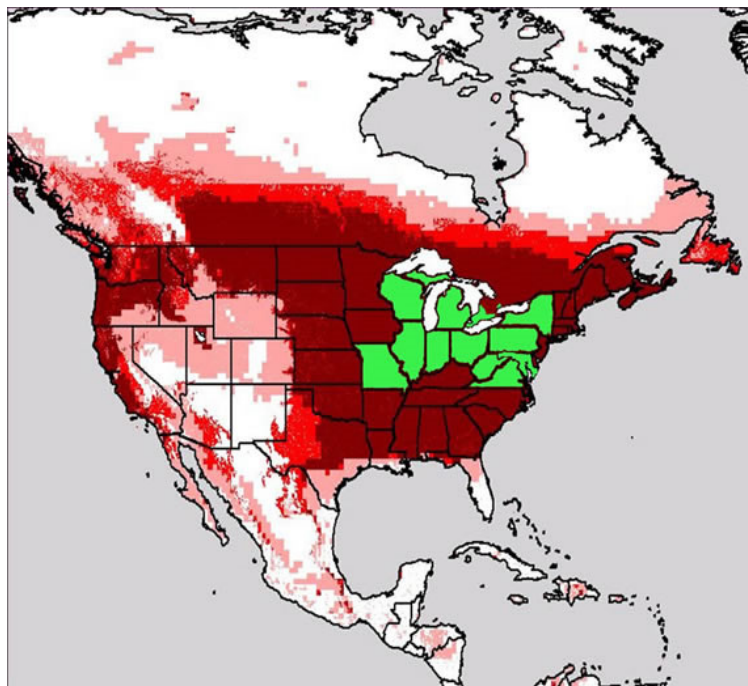


Figure 3. Current Distribution and Anticipated Spread of Emerald Ash Borer in North America The current distribution of emerald ash borer (up to 2008) is indicated in green; the first Canadian discovery was in Ontario in 2002. The potential future distribution is shown in red (based on niche modeling by Daniel A. Kluza and Eduard Jendek [used with permission])²⁸.



ROLE OF GENOMICS IN FOREST HEALTH MANAGEMENT

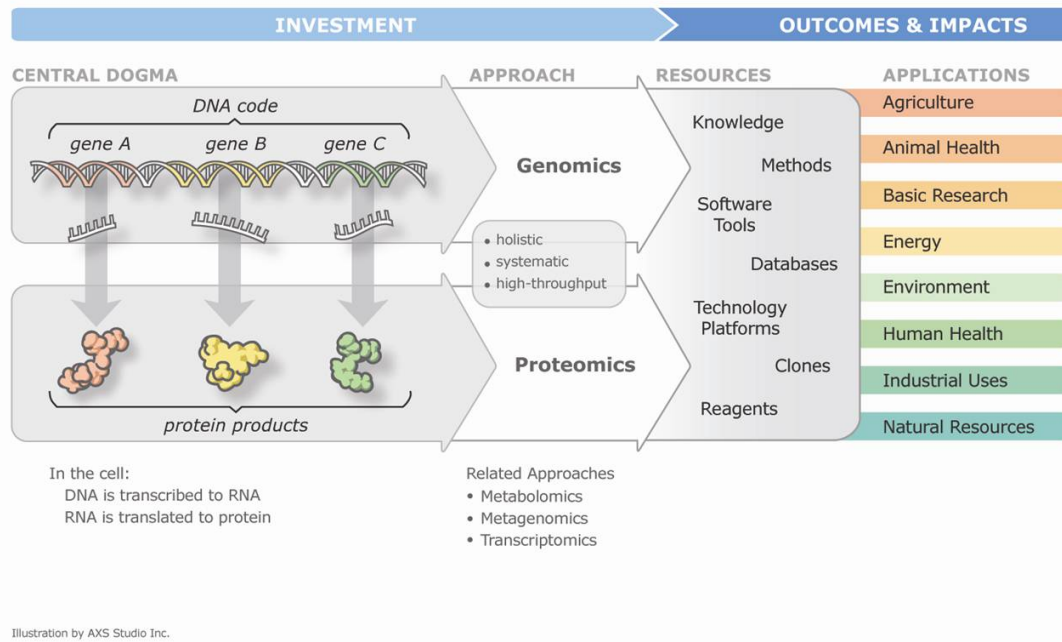
New strategies stemming from research and development will help to meet the challenges facing our forest industry, assist in sector transformation, and integrate with traditional forest management activities to ensure a prosperous and sustainable future for Canada's entire forest sector. The genome sciences³⁰ are promising to deliver increasingly affordable new technologies on which such strategies can be based. They provide an unprecedented level of understanding of pests and diseases, their impacts on host trees, and on the wider forest ecosystem. Genomics-enabled preventative and mitigation approaches to pest problems can be used in concert with currently available traditional techniques and socio-economic interventions, such as:

- ◆ Risk analysis activities
- ◆ Support for decision-making and policy development, including:
 - Regulatory structures to encourage and assist in pest containment, such as those currently in place for the emerald ash borer, Asian long-horned beetle, brown spruce longhorn beetle, sudden oak death pathogen, and *Sirex* woodwasp
 - Through social sciences and humanities research, ensuring a coordinated response from the grass-roots community to the national level, as well as between communities, government, and industry
- ◆ Introducing and defining trade controls
- ◆ Pest monitoring and phytosanitary certification
- ◆ Breeding programs (selecting for resistance, etc.).

Genomic technologies and the genomics research paradigm (see Figure 4) that include genomics, proteomics, and metabolomics, along with bioinformatics³⁰, can be used to identify genes, genetic variations, and molecular pathways to understand biological processes and their interactions with environmental factors.

³⁰ The genome sciences (also called “genomics” in this document) include: genomics (the study of the complete genome of an organism, i.e., all hereditary information encoded in the DNA); transcriptomics (the study of the transcriptome, the complete set of RNA transcripts produced by the genome at any one time); proteomics (the study of the full or partial set of proteins encoded by a genome); metabolomics (the study of the metabolic products and networks of an organism); metagenomics (the identification of all the genetic material present in a sample from a complex environment [e.g., soil, water, gastrointestinal tract], consisting of the genomes of many individual organisms); systems biology (a combination of the abovementioned technologies to understand the relationship between and function of all components of a biological system); bioinformatics (the science of informatics as applied to biological research).

Figure 4. Genomics Research Paradigm Investment into high throughput holistic and systematic research in genomics and proteomics generates knowledge and resources that persist even after the research project ends. These will lead to a broad range of benefits in the medium and long time frame.



Addressing Changing Ecosystems Due to Climate Change

Climate change is an overarching issue for the Canadian forest sector. Genomics research can help breeders and forest managers respond to the challenges of changing environmental conditions by:

- ◆ Mapping the genetic diversity within and between different tree species
- ◆ Identifying genes that confer hardiness, adaptation, etc., thereby improving our understanding of plant adaptation to different climates, soils, and conditions
- ◆ Identifying genes that confer resistance to pests and pathogens of concern
- ◆ Identifying genes/processes affecting commercially-desirable properties (aesthetic, structural, etc.)
- ◆ Identifying processes/genes affecting plant reproduction for efficient breeding
- ◆ Increasing basic knowledge of pests and pathogens including life cycle and incursion pathways that will allow the development of bio-control agents targeting essential biological components.

Minimizing the Effects of Invasive Pests and Other Organisms

By increasing knowledge and understanding, genomics research can help to provide tools that can aid in the detection of stressed or infected trees, accurately identify invading organisms, treat and control the infestation, and monitor for invasive pests and diseases. The rapid and accurate identification of a causal organism is critical to allow the implementation of optimal control strategies and minimize the damage. Specifically, genomics can:

- ◆ Play an important complementary role in monitoring and detecting/identifying pathogens and pests for regulatory purposes and provide a means to detect an infection before visual symptoms appear
- ◆ Following additional foundational research on host specificity, integrate with existing tools to identify and classify species and strains of insects and pathogenic microbes in regard to host specificity and distribution
- ◆ Illuminate molecular interactions that encode the relationship between the tree, pest, and other environmental factors. Such molecular dynamics of host-parasite interactions are currently being studied by Canadian researchers working on the mountain pine beetle epidemic. Lessons learned from this complex project can be applied to other projects
- ◆ Employ genetic barcodes to efficiently track pest migration as a critical population process. DNA base species identification tools will allow broader coverage and augment the identification of sources of long-distance dispersal events to elucidate pathways of invasion and quantification of movement/dispersal in critical, density-dependent processes such as mating, survival, etc.
- ◆ Identify markers for resistance genes that could then be surveyed and mapped over landscape scales
- ◆ Provide deeper molecular knowledge of the pests as they relate to patterns and dynamics of the infestations (population dynamics)
- ◆ Identify genes and other genomic regions that confer resistance or other adaptive traits to specific pests
- ◆ Identify the genetic weaknesses of pathogens and insects, supplying targets for new or supplemental health management tools, including biocontrol agents
- ◆ Aid successful breeding programs by developing biomarker tools that can be used to find resistant or other commercially important characteristics in seedlings; these seedlings can then form the basis of new stands.

Improving Overall Forest Health

Genomics can also help to support the risk analysis framework developed by the Canadian Council of Forest Ministers in collaboration with the Canadian Food Inspection Agency (CFIA) and the Canadian Forest Service (CFS) of Natural Resources Canada in their National Forest Pest Strategy³¹. For example, within the Science and Technology component that aims to strengthen the link between technology users and providers, areas of focus will include development of detection, monitoring and response tools, as well as support for tree breeding and tree improvement for increased host resistance.

Industrial Use of Damaged Trees

Damaged trees still have industrial utility, particularly in the short- to medium-term. Trees killed by pests need to be processed within a few years if they are to be converted to solid wood products. Wood waste and trees that are too damaged for other uses can be used as biofuel or bio-chemical feedstock. Genomics offers numerous opportunities to the biofuel and biocomposite industries, thereby helping to support the renewal of the rural economy³². For example, genomic techniques can identify enzymes with enhanced cellulolytic properties (e.g.,

³¹ National Forest Pest Strategy. <http://canadaforests.nrcan.gc.ca/articletopic/187>. Accessed May 5, 2009.

³² FPAC press release: www.fpac.ca/en/media_centre/media_kits/dec-16-08/12-15-2008---E---Press-Kit---FINAL-.pdf. Accessed May 27, 2009.

from microbial or insect sources) to more effectively convert the waste to fuel or identify molecular bonds and binding compounds for composites³³.

Understanding and Addressing the Social Context of Forest Genomics

Given the social, cultural, and economic importance of forestry, social science and humanities research will also play an important role in understanding and addressing the social, economic, and environmental impact of Canada's forest pests. Potential issues include:

- ◆ Conducting cost/benefit analyses of forest genomics approaches
- ◆ Understanding how genomics tools will complement existing forest management strategies in response to pests, particularly exploring where genomics tools could play the greatest role
- ◆ Assessing the economic impact of genomics research on mitigating the forestry pest problem
- ◆ Understanding public perceptions about the role genomics might play in managing forest pests
- ◆ Assessing the cultural significance of forests and understanding how this cultural significance might influence the acceptance of genomics tools
- ◆ Exploring legal questions surrounding the deployment of genomics-enabled solutions or ownership of novel tree clones
- ◆ Understanding: 1) the policy framework that will govern genomics tools, and 2) how this framework will respond to new technological developments.

THE SOCIOECONOMIC PROMISES OF CONTINUING GENOMICS RESEARCH

Research priorities detailed within this document will create a knowledge base and additional complementary tools for sustainable forest management. By coordinating our efforts nationally, we will address the challenges by capitalizing on Canadian genomics strengths and accessing industry resources. These activities will help to minimize the threats to our largest industry and one of the most important components of the country's social fabric. The following examples describe the intended outcomes of ongoing research.

Projects Targeting Multiple Pest Species

Research to help mitigate the effects of pests in our forests is underway and the CFHGI proposed to build upon and expand these efforts. Examples for pests as a whole include:

- ◆ DNA species identification. DNA barcoding based species identification is becoming a cost effective tool for detection, monitoring, and management of invasive species. The Barcode of Life Data (BOLD) system developed at the Canadian Centre for DNA Barcoding in Guelph provides a very realistic, practical, and flexible framework for species identification. BOLD currently hosts DNA species barcodes for over 584,000 specimens representing more than 55,000 species³⁴. A full implementation of DNA barcoding as a means of species

³³ Jeng R, Huang C, Sain M, et al. Starch-like exopolysaccharide produced by the filamentous fungi *Ophiostoma ulmi* and *O-novo-ulmi*. *Forest Pathology*. 2007;37(2): 80-95.

³⁴ Ratnasingham S, Hebert P D N. BOLD: The Barcode of Life Data System (www.barcodinglife.org). *Mol. Ecol. Notes*. 2007; 7:355-364. www.barcodinglife.org accessed May 13, 2009; Armstrong KF, Ball SL. DNA barcodes for

identification could enhance the Canadian Food Inspection Agency's (CFIA) and other organizations' prevention, response, and management (containment, eradication, and control) strategies for these pests and pathogens, translating into better protection of Canada's forestry resource base.

- ◆ Genomic surveys of pests' natural pathogens and diseases. Forest pest insects are often stricken with fungal, viral, or bacterial infections that do not necessarily produce overt disease symptoms. Using large scale sequencing, pathogen-specific sequences can be discovered in hosts, and help in identification of novel control agents. From genome characterization of pathogens to their registration for application in the field, enhanced efforts in this area could lead to success stories like the Abietiv™ fir sawfly viral control agent (described below), developed by the CFS and Sylvar Technologies. Pests under study include the emerald ash borer, the Asian long-horned beetle, and the brown spruce longhorn beetle.
- ◆ Genomic markers. The identification of genomic markers (essentially expressed genes) that are unique signatures during pest infestation could be used as an aid to diagnostic monitoring of tree health. Gene targets related to pest resistance will also improve efficiency of breeding for resistance and will speed up associations between DNA markers. Validation (by functional genomics) of these markers will make them more reliable and should progress technology transfer to stakeholders (e.g. industry and government agencies).
- ◆ Epidemic management strategies. Using data from current pest epidemics, Canadian researchers are developing strategies for preparing for, or even preventing, future epidemics. Prevention of an epidemic such as the mountain pine beetle would save billions of dollars worth of forestry products and allow the continued employment of thousands of people.
- ◆ Population genetics. For some pests, population genetic studies will generate knowledge on population diversity, distribution, and intra- and inter-dynamics, allowing better monitoring and containment of their spread.

The Spruce Budworm: A Model System for Forest Genomics

The spruce budworm devastated the forests of Ontario, Quebec, New Brunswick, and Nova Scotia in the 1970s and 1980s during a 15-year long epidemic. A major new outbreak, which may be related to climate change due to its unusual pattern, has been in progress since the mid 1990s³⁵ (see Figure 1). Genomics research on this pest and its viral pathogens and host tree species has so far produced vital resources for understanding complex interactions between this budworm and its environment. These resources include:

- ◆ A compendium of spruce budworm expressed sequence tag (EST) data and a microarray platform based on these data
- ◆ The complete nucleotide sequences of two spruce budworm baculoviruses that could be used for the development of biocontrol agents
- ◆ A collection of multiple spruce budworm cell lines for the study of budworm viruses and their large scale production *in vitro*

biosecurity: invasive species identification. *Philos Trans R Soc Lond B Biol Sci.* 2005 October 29; 360(1462): 1813–1823. <http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=1609225>. Accessed May 28, 2009; Ball SL, Armstrong KF. DNA barcodes for insect pest identification: a test case with tussock moths (Lepidoptera: Lymantriidae). *Can J For Res.* 2006; 36:337-350.

³⁵ Natural Resources Canada. <http://canadaforests.nrcan.gc.ca/articletopic/180>. Accessed May 13, 2009.

- ◆ Knowledge of host tree (white spruce) genomics with a focus on the mechanisms involved in insect defense³⁶.

Insect virus genomics research has already resulted in the development of a pest-controlling baculovirus. Sold under the name Abietiv™, this virus is environmentally safe and specifically targets the destructive fir sawfly to reduce outbreak damage (see below for more information). Its environmental safety and control success is prompting the exploration of other related baculoviruses³⁷, in particular viruses that can develop into epizootics (temporary but widespread outbreak of disease) in host populations. One area of research involves the molecular modification of viruses infecting the spruce budworm, including a baculovirus modified to express the spruce budworm transcription factor CHR3. Infection with this virus results in poor development of larval mouthparts, preventing the budworm from foraging. This modified baculovirus is currently being presented to the Pest Management Regulatory Agency as a test case for registration under the *Pest Control Products Act of Canada*.

Mitigating the Mountain Pine Beetle Threat

Genomic research associated with the mountain pine beetle epidemic, as illustrated in Figure 2, is underway. The genome of a fungus linked to the beetle is the first forest tree disease-causing fungus to be sequenced in Canada. Host response to the mountain pine beetle is varied, with some trees reacting more severely to the beetle and its associated fungal pathogen than others. Although heritabilities for host resistance are low (in the range of ~20%, as with many other traits under strong natural selection), they are still biologically and commercially significant. Genomic research on the mountain pine beetle will support:

- ◆ The identification and characterization of resistance genes in the host
- ◆ The identification of variations in beetle populations that impact infection risks, such as differences in temperature-dependent rates of development, greater cold tolerance, etc., that would affect climate suitability predictions
- ◆ The identification of mechanisms that control symbiotic relationships between the beetle and its associated tree-killing fungi.

The resulting data will offer opportunities for the development of biomarker tools for direct application in forest management and future control of the beetle. For example, the tools could be used by tree breeders to select resistant or otherwise adapted lines in a far more timely manner than at present: in three years rather than 15-20 years.

Genomics is also being incorporated into risk assessment models. The current Tria Project³⁸ <http://www.thetriaproject.ca/index.php> is developing genomics resources for the three components of the mountain pine beetle system: the pine tree host, the bark beetle vector, and the fungal pathogen. Structural, functional, and physiological genomics will be incorporated into environmental risk models to assess the relative likelihood of the epidemic moving east from the currently affected lodgepole pine forests into the jack pine of Canada's extensive boreal forests. These risk models may be used to identify strategic intervention or mitigation points on the

³⁶ Godard K-A, Byun-McKay A, Levasseur C, Plant A, Séguin A, Bohlmann, J. Testing of a heterologous, wound- and insect-inducible promoter for functional genomics studies in conifer defense. *Plant Cell Reports*. 2007; 26(12): 2083-2090. <http://www.springerlink.com/content/q768755u72202801/>.

³⁷ Moreau G, Lucarotti C.J. A brief review of the past use of baculoviruses for the management of eruptive forest defoliators and recent developments on a sawfly virus in Canada. *The Forestry Chronicle* 2007;83:105-112.

³⁸ www.thetriaproject.ca.

landscape, inform socioeconomic models of feedstock or forest product use, and identify areas of higher concern in a changing climate.

Investigating the Emerald Ash Borer

Identification, monitoring, and prevention of impacts caused by the emerald ash borer, which is expected to spread throughout Ontario and beyond (see Figure 3), would be augmented by the application of genomic studies. Genomics research is currently being conducted by the CFS to improve our understanding of host tree detection by this insect. Host plant chemicals play an important role in aiding insects as they forage to suitable host trees, and in coordinating reproductive activities. At present, neither the host proteins responsible for producing these compounds nor the insect proteins that “capture” and process these compounds and influence behaviour are known in this species. The “sensory genomics” of emerald ash borer appendages (e.g., antennae and legs) used to detect host compounds will aid in understanding the impressive ability of this pest to target ash trees in a complex environment. Emerald ash borer genomics will also shed light on chemical communication systems used in reproduction (i.e., the use and perception of pheromones). Such knowledge could be integrated with other current forest management practices to detect the beetle at invasion fronts, or mitigate the beetle’s impact.

Currently at an early stage, this type of research will be instrumental in devising methods to make trees less attractive to the beetle (e.g., by blocking host volatile production) and/ or by derailing the beetle’s chemical communication system. Furthermore, as with the mountain pine beetle, genes for tree resistance could be screened at an accelerated rate, identifying individual trees for selection and production in commercial nurseries.

Summary of the Socioeconomic Outcomes of Genomics Research

By integrating with traditional forestry tools, ongoing forestry genomics research promises knowledge that could lead to numerous benefits and significant impact on the future of Canadian forests. Some of the potential socioeconomic successes are summarized in Table 2.

Table 2. Summary of Outcomes and Applications of a Sample of Ongoing Forest Health and Related Genomics Research Projects

Project Title, URL, and Targeted Species	Intended Outcomes	Applications	Milestones to Reach Outcomes and Application
Barcode of Life (www.barcodinglife.org) Multiple plant and animal species	A practical and flexible framework for species identification. The system is based on sequencing of standardized genetic regions that allows species discrimination.	Invasive alien species detection/ identification and low cost monitoring of pest outbreaks and distribution.	<ul style="list-style-type: none"> • Completion of the Canadian forest pest and pathogen registry of DNA Barcodes • Implementation and adaptation of DNA barcoding as a species identification tool in federal and provincial labs and monitoring stations
Molecular Screening for Pathogens of Indigenous and Introduced Coleopteran Forest Pests Genomic surveys of various pest pathogens	Identification of novel pest insect pathogens; evaluation of their potential as pest control products	Novel pest control products (e.g. bacteria, viruses and/or fungi)	<ul style="list-style-type: none"> • Screening of host insects. • Partial or full genome sequencing of pathogens (e.g., viruses) • Evaluation of control potential of the new pathogens
Treenomix Conifer Forest Health Project; www.treenomix.ca White pine weevil; spruce weevil	Tools and knowledge in support of breeding for improved resistance of Sitka spruce and white spruce against the white pine weevil	Tree breeding	<ul style="list-style-type: none"> • Genomics resources for spruce host trees and weevils • Functional genomics information for spruce – weevil interactions • Molecular markers
Various projects on the spruce budworm; no specific URL ³⁹ Spruce budworm	Increased knowledge in spruce budworm biology, population biology	Novel pesticides & complementary management options; integration of genomics/genetic knowledge with population dynamics models	<ul style="list-style-type: none"> • Further genome and transcriptome characterization of spruce budworm, its pathogens and its host tree species • Functional testing of genes for the creation of recombinant spruce budworm baculovirus strains
The Tria Mountain Pine Beetle System Genomics Project; www.thetriaproject.ca Mountain pine beetle (MPB), associated fungal pathogens	Genomic resources and improved knowledge for the beetle-fungal-tree host interactions in the mountain pine beetle epidemic	Augment forest pest management practices by improving the accuracy of predictive environmental risk models, and developing diagnostics (biomarker tools) for forest pests	<ul style="list-style-type: none"> • Complete genome sequence of the beetle-associated fungal pathogen • Transcriptome sequences for the MPB and pine tree host • Identification of genes linked to bark beetle fitness, fungal pathogenicity, and tree resistance to the pathogen • Incorporation of genomic information into ecological risk models to support decision-making around short-term outbreak progression and long-term forecasts of MPB spread

³⁹ For a listing of some projects, see <http://warehouse.pfc.forestry.ca/HQ/28124.pdf>. Accessed June 29, 2009.

SUCCESS OF PAST CANADIAN INVESTMENTS IN FORESTRY GENOMICS

Genomic-based tools have already been developed and used successfully by Canadians to help mitigate the effects of forestry insects and pathogens.

- ◆ A kit was developed by the CFS to monitor the canker that causes sudden oak death before the disease moved from the US to Canada. It is being used by the CFIA and US Department of Agriculture-Animal and Plant Health Inspection Service (USDA-APHIS) to certify that Canadian nurseries are free of the disease, thereby allowing Canadian producers to export their materials⁴⁰.
- ◆ Using genomics, scientists at the CFS characterized and subsequently commercialized (via Sylvar Technologies) the naturally occurring insect nucleopolyhedrovirus as a forest pest management product (Abietiv™). \$750,000 worth of Abietiv™ was sold and successfully sprayed over large parts of Newfoundland and Labrador against balsam fir sawfly in 2006⁴¹. The virus not only resulted in the collapse of infestations, but an epizootic was established that kept the insect under control for a number of years⁴². Furthermore, Sylvar employs research scientists as well as laboratory and field support personnel, adding high value jobs in Fredericton, New Brunswick.
- ◆ Scientists at the CFS have identified blister rust resistance genes in western white pine. Pollen from major gene resistant (Cr2) trees is now used to create “clean” seedlings for use in coastal reforestation in BC⁴³.
- ◆ Researchers have identified the genetic basis of elicitor compounds induced in elm trees when attacked by Dutch elm disease carried on European elm bark beetles and their fungal symbionts. They have used the information to develop ‘vaccine’ tactics to immunize healthy elms with avirulent disease strains. This strategy is currently undergoing commercial development in field trials on the leading edge of the Dutch elm disease infestation to prevent its devastation of elm trees in western Canada⁴⁴.

CANADA’S LEADERSHIP AND STRENGTHS

World-Class Leadership

Canada’s forestry genomics researchers are world leaders, particularly in the area of conifer and forest pest research. The Treenomix Conifer Forest Health Project⁴⁵ was the first large-

⁴⁰ Seeing the forest through the genes. Natural Resources Canada. <http://canadaforests.nrcan.gc.ca/articletopic/133>. Accessed May 28, 2009.

⁴¹ Cuddeford V. Good news for Canadian biocontrol: Registration of Abietiv, a new made-in-Canada bioinsecticide. *BioControl Files: Canada’s Bulletin on Ecological Pest Management* 2006; November. www.biocontrol.ca/pdf/Bio8EN-Final.pdf; www.sylvar.ca/content/13058. Accessed May 6, 2009.

⁴² Arif B. Genomics of the spruce budworm and its viral pathogens, and the pursuit of bioactive molecules as spin-offs. Genomics for future forests symposium report. Natural Resources Canada Canadian Forest Service. 2006; 41-44.

⁴³ Zeglen, S., Hunt R, Cleary M. British Columbia’s forests: White Pine Blister Rust Forest Health Stand Establishment Decision Aid. *BC Journal of Ecosystems and Management* 2009; 10(1):97–100. www.forrex.org/jem/ISS50/vol10_no1_art9.pdf. Accessed May 28, 2009.

⁴⁴ Scheffer RJ, Voeten JGWF, Guries RP. Biological control of Dutch elm disease. *Plant Disease*. 2008; **92**, 192-200; Nasmith C, Jeng R, Hubbes M. A comparison of *in vivo* targeted gene expression during fungal colonization of DED-susceptible *Ulmus Americana*. *Forest Pathology*. 2008; 38(2): 104-112; Coghlan A. A jab for trees - A vaccine will make it easier to control Dutch elm disease. *New Scientist*. 1998;160 (2164):7; Trees to be vaccinated against Dutch elm disease. CTV. Updated Sat. Jun. 6 2009 10:02 PM. http://www.ctv.ca/servlet/ArticleNews/story/CTVNews/20090524/dutch_elm_090524/20090606?hub=SciTech.

⁴⁵ www.treenomix.ca.

scale, international, and integrative forest health genomics project led by Canadian researchers. Furthermore, the CFS has a strong network of scientists working on insect population dynamics, climate change research, and carbon budget modeling. CFS research in New Brunswick, Quebec, Ontario, and BC covers pest insect genomics and applied tree resistance genomics.

The excellence of Canadian forest genomics researchers has been recognized by other countries with major forest assets, such as Brazil, Norway, Sweden, and the US, as well as Austria, Belgium, China, France, Germany, Italy, the Netherlands, Spain, South Africa, Thailand, and the UK⁴⁶. Large scale collaborative projects have been conducted with, among others, Umea Plant Sciences Centre (Sweden), the UK Forestry Commission, the University of California Davis, and the Max Planck Institute for Chemical Ecology (Jena, Germany). Canadian scientists have been and currently are involved in global projects related to two major tree species in Canadian forestry, spruce and poplar, and participated in the recent international sequencing of black cottonwood genome⁴⁷. Canadian scientists are also part of many international collaborative projects involving the biology and genomics of baculoviruses (viruses that mainly infect insects).

Forestry Genomics Capacity from the Atlantic to the Pacific

Genome Canada, the regional Genome Centres⁴⁸, the Canadian Forest Service of Natural Resources Canada, the CFIA, and the provincial ministries of forests have actively supported large scale forestry genomics research over the past nine years (Appendix 2). Investments from universities, research institutes, NSERC, other federal departments and agencies, companies, and others have created additional genomics capacity and expertise applicable to forestry. Capabilities have been underpinned by Canada's internationally competitive large scale technology platforms and R&D centres (Appendix 3). The research has resulted in basic structural and functional data that are now being applied to novel tools that can be used in conjunction with traditional forest management techniques, as indicated above.

A selection of Canada's key genomics researchers in forest health and related areas are listed in Appendix 4. These include scientists working on biofuels from wood waste, as well as those working specifically on forest health. Canadian forest researchers continue to build upon existing data to further elucidate the complex relationships between trees, insects, pathogens, and environmental conditions, and create new forest management tools. By collaborating more extensively, the challenges to the forest industry can be addressed far more effectively than working alone.

NEXT STEPS TOWARD SUCCESS

The current document identifies three critical forest pest issues that, among many others discussed, show a strong potential for the integration of genomics tools into current management practices. To enable this, the authors of this document feel that the expertise and capacity exists for interdisciplinary teams of researchers to undertake in the next 3-5 years up to

⁴⁶ Krell P. Canadian research involvement in international insect pest and pathogen projects. Genomics for future forests symposium report. Natural Resources Canada Canadian Forest Service. 2006; 37-39.

⁴⁷ Tuskan, G.A. et al. The genome of black cotton wood, *Populus trichocarpa*. *Science*. 2006; 313: 1596-1604.

⁴⁸ Genome BC, Genome Alberta, Genome Prairie, Ontario Genomics Institute, Genome Québec, Genome Atlantic.

5 large-scale demonstration projects with overall budgets of \$5-10 million per project. Such Projects could arise in a number of ways such as:

1. A need is identified by the Canadian government, one or more Canadian Provinces, Genome Centres, or the forest industry to address any major forest health threat. If it is decided that genomics-based solutions could ameliorate the threat, then project proposals would be solicited, subjected to peer review and managed by the funding partners.
2. A Request for Applications (RFA) is issued by a provincial, national or international funder in which forest genomics is an eligible subject area.
3. An international consortium of researchers and funding agencies recognizes the value to bundling expertise and resources in the area of genomics to address common forest health threats and a suitable project emerges.

The key to success of any these Projects would be the integration of expertise from all available sources and the engagement of the Canadian Forest Service (or equivalent international forest agency), provincial forest management groups, and the forest industry. These Projects would be required to have a clear set of deliverables and timeframes to ensure benefits to the end-users. Additionally, Projects would need to include strong outreach to affected community groups, First Nations, regional development organizations, and other involved stakeholders.

In summary, advances in genomics have made it possible to address important forest health issues. However, coordination of research efforts, provincially, nationally and internationally will be critical to make most efficient use of limited financial resources. This document has already identified some areas that could benefit from such coordination and laid a foundation for future forest genomics research.

APPENDIX 1. CURRENT AND PREDICTED REGIONAL FOREST HEALTH THREATS

This listing of current and predicted regional forest health threats for the Atlantic provinces, Quebec, Ontario, Manitoba, Saskatchewan, Alberta and British Columbia was presented at the CFHGI Workshop on March 31, 2009. This is not an exhaustive list, the threats listed are not necessarily in order of importance, and the list should not be referenced for technical or scientific accuracy. The three pest species identified in this White Paper as particularly serious that could be used as models by genomics researchers to address global forest health issues are underlined.

ATLANTIC PROVINCES

- Balsam fir sawfly – Newfoundland
- Hemlock looper – Newfoundland and Labrador
- Jack pine budworm – Nova Scotia
- Brown spruce longhorn beetle – Nova Scotia
- Spruce budworm (predicted) – currently in eastern Canada
- Gypsy moth (predicted) – currently in eastern Canada
- Emerald ash borer (predicted) – found in Great Lake states and east, Ontario and Québec
- Asian long-horned beetle (predicted) – currently in Ontario
- Hemlock and balsam wooly adelgids (predicted) – found on eastern seaboard Canada
- European pine shoot beetle (predicted)
- Beech bark disease (predicted)

QUEBEC

- Large aspen tortrix
- Satin moth
- Eastern tent caterpillar
- Spruce budworm
- Emerald ash borer
- Hemlock looper
- Die-back of oak
- Anthracnose
- Gray mould
- Needle and leaf rust
- White pine blister rust
- Septoria canker
- Butternut canker
- Scleroderris canker
- European pine shoot beetle (predicted)
- Beech bark disease (predicted)
- Hemlock woolly adelgid (predicted)
- Gypsy moth (predicted)

ONTARIO

- Spruce budworm (predicted)

- Jack pine budworm
- Tent caterpillar
- Emerald ash borer
- Asian long-horned beetle
- *Sirex* woodwasp
- Elm bark beetles
- Gypsy moth
- European pine shoot beetle (predicted)
- Beech bark disease (predicted)
- Hemlock woolly adelgid (predicted)
- Gypsy moth (predicted)
- Fall and spring cankerworm
- Dutch elm disease
- *Armillaria* root disease
- White pine blister rust
- Sudden oak death
- Butternut canker
- *Septoria* Canker
- Invasive plants (dog-strangling vine; garlic mustard; knotweed; buckthorn)

MANITOBA

- Spruce budworm
- Jack pine budworm
- Western gall rust
- *Armillaria* root rot
- Dwarf mistletoe
- Dutch elm disease
- Fall and spring cankerworm
- Elm bark beetles (predicted)
- Emerald ash borer (predicted)
- Mountain pine beetle (predicted)
- Eastern larch beetle (predicted)

SASKATCHEWAN

- *Septoria* disease
- Mountain pine beetle
- Elm bark beetles (predicted)
- Dutch elm disease (predicted)

ALBERTA

- Mountain pine beetle
- Western spruce budworm
- Forest tent caterpillar
- Elm bark beetles (predicted)
- Dutch elm disease (predicted)

- Invasive plants

BRITISH COLUMBIA

- *Commandra* blister rust
- White pine blister rust
- *Armillaria* root disease
- Laminated root rot
- *Tomentosus* root rot
- *Dothistroma* needle blight
- Hemlock looper
- White pine weevil
- Warren root collar weevil
- Bark beetles (mountain pine beetle, spruce beetle, Douglas-fir beetle, western pine beetle, western balsam bark beetle, pine engraver)
- Western spruce budworm
- 2-yr cycle budworm
- Blackheaded budworm
- Tussock moth
- Gypsy moth
- Forest tent caterpillar

APPENDIX 2. CURRENT AND PAST LARGE-SCALE CANADIAN GENOMICS FORESTRY PROJECTS

Project Name	Funders	Dates	Deliverables	URL
Arborea I: Functional Genomics of Regulation in Forest Trees	Genome Canada, Genome Quebec, Natural Resources Canada (Canadian Forest Service), Genomics R&D Initiative	2002-2005	The development of genomic methods and tools to enhance genetic selection and breeding of softwood forest trees	www.arborea.ca
Arborea II: Genomics for Molecular Breeding in Softwood trees	Genome Canada, Genome Quebec, Genome Alberta, Natural Resources Canada (Canadian Forest Service), Genomics R&D Initiative	2006-2009	Will develop tools and protocols making it possible to select well adapted high-performance spruce trees with better-quality woods	www.arborea.ca
Genomics of the Spruce Budworm and its Viral Pathogens	Genome Canada, Ontario Genomics Institute, Natural Resources Canada (Canadian Forest Service), Genomics R&D Initiative, Agriculture and Agri-Food Canada	2002-2005	Creation of genomic tools and knowledge leading to control of the spruce budworm, one of Canada's most devastating pests	http://pestgenomics.org/ ⁴⁹
Identification of control agents and determination of factors	Canadian Food Inspection Agency, Natural Resources Canada (Canadian Forest	2006-2010	1. Screening methods for determining susceptibility in plant hosts 2. <i>In vitro</i> & <i>in vivo</i> evaluation of	

⁴⁹ This website is correct to 2005 and is currently being updated.

affecting the pathogenicity and host range of <i>Phytophthora ramorum</i>	Service), Genomics R&D Initiative, Agriculture and Agri-Food Canada		biological control agents and chemical fungicides for management of <i>P. ramorum</i> . 3. Identification of factors affecting the fungi pathogenicity and sporulation potential.	
The Tria Mountain Pine Beetle System Genomics Project (Mountain Pine Beetle Epidemic – Using Genomics of the Interacting Bark Beetles, Fungal Pathogens and Host Pine Trees to Improve Forest Ecological Risk Models)	Genome Alberta, Genome BC	2008-2009	Expect: 1. First complete genome sequence for a tree-killing bark beetle-associated fungal pathogen 2. Transcriptome sequences for the MPB and the pine tree host 3. Identification of genes that are linked to bark beetle fitness, fungal pathogenicity, and tree resistance to the pathogen 4. Application of information from (1)-(3) to enhance forest pest management practices by improving the accuracy of predictive environmental risk models, and developing diagnostics for forest pests and diseases	www.thetriaproject.ca
Treenomix I:	Genome Canada, Genome BC	2001-2005	Developed first draft genome sequence	www.treenomix.ca

<p>Mechanisms of Wood Formation and Pest Resistance in Forest Trees Using Poplar, Spruce and Arabidopsis</p>			<p>and annotation of the poplar genome; being used to support breeding programs in the BC Ministry of Forestry and inform forestry programs across Canada and internationally</p>	
<p>Treenomix II: Conifer Forest Health Genomics</p>	<p>Genome Canada, Genome BC, Umea Plant Sciences Centre (UPSC), Max Planck Institute for Chemical Ecology (Jena, Germany), UC Davis, UK Forestry Commission, BC Ministry of Forest and Range</p>	<p>2006-2009</p>	<p>Identify the underlying genetic mechanisms of resistance to biotic disturbance (for example resistance to insects and pathogens) and adaptation to abiotic stress</p>	<p>www.treenomix.ca</p>

APPENDIX 3. CANADA’S LARGE-SCALE S&T PLATFORMS, R&D CENTRES, AND GENOMICS RESOURCES RELEVANT TO FOREST HEALTH

Centre for Applied Genomics, Toronto ON	Provides support for innovative research and service in genomics. Maintains core facilities for (i) DNA Sequencing and Synthesis, (ii) Cytogenomics and Genome Resources, (iii) Gene Expression and Microarrays, (iv) Genetic and Statistical Analysis, and (v) Biobanking and Databases	www.tcag.ca
Genome BC Genomics Platform at Michael Smith Genome Sciences Centre, BC Cancer Agency (BCCA), Vancouver, BC	High-throughput Sanger and next generation Illumina Sequencing; physical mapping; and bioinformatics research facilities. Also has proteomics, array, expression cloning, and high-throughput virtual screening technologies	www.bcgsc.ca/platform/
Genome BC Microarray Platform at The Prostate Centre, Vancouver General Hospital, BC	Offers access to a comprehensive set of microarray researchers and services	www.microarray.prostatecentre.com
Integrated and Distributed Bioinformatics Platform for Genome Canada at Sun Centre for Visual Genomics, Calgary, AB	Explores leading edge research to develop new approaches to the understanding of genomic data; provides services to Genome Canada funded initiatives and other global research initiatives	http://gcbioinformatics.ca/
McGill University and Genome Quebec Innovation Centre, Montreal Qc	Offers research and services in high-throughput genomics, proteomics and bioinformatics	www.genomequebecplatforms.com/mcgill/home/index.aspx
Technology Development, based at UBC and the BCCA, Vancouver BC	Performs research, technology, and engineering development for the genomics community	www.genometech.physics.ubc.ca
UVic - Genome BC Proteomics Centre, Victoria BC	Provides research, service and support for protein identification, characterization, and quantitation for biomarker discovery and validation	www.proteincentre.com

APPENDIX 4. SELECTED FOREST HEALTH AND BIOFUEL GENOMICS EXPERTISE IN CANADA

Researcher	Affiliation	Species	Relevant Projects
BC			
Aukema, Brian	Natural Resources Canada, Canadian Forest Service (NRCan-CFS)/ UNBC	Pine, Bark Beetle	Mountain Pine Beetle (www.thetriaproject.ca)
Bohlmann, Jorg	UBC	Spruce, Pine, Bark Beetle	Treenomix I and II (www.treenomix.ca); Mountain Pine Beetle (www.thetriaproject.ca); Conifer Forest Health (www.treenomix.ca)
Breuil, Colette	UBC	Pine, Bark Beetle	Mountain Pine Beetle (www.thetriaproject.ca)
Constabel, Peter	University of Victoria	Poplar	Poplar-pest interactions (http://web.uvic.ca/~cpc/)
Douglas, Carl	UBC	Poplar, Spruce, Arabidopsis	Treenomix I (www.treenomix.ca)
Ekramoddoullah, Abul	NRCan-CFS	Western white pine	Resistance genes for white pine blister rust
Ei-Kassaby, Yousry	UBC	Douglas fir, yellow cedar	Molecular breeding
Ellis, Brian	UBC	Poplar, Spruce and Arabidopsis	Treenomix I (www.treenomix.ca)
Hamelin, Richard	NRCan-CFS	Pine, Bark Beetle	Mountain Pine Beetle (www.thetriaproject.ca)
Huber, Dezene	UNBC	Pine, Bark Beetle	Mountain Pine Beetle (www.thetriaproject.ca)
Keeling, Christopher	UBC	Pine, Bark Beetle	Mountain Pine Beetle (www.thetriaproject.ca)

Mansfield, Shawn	UBC	Spruce, poplar	Bioenergy feedstock, fibre properties, sequestration of carbon & biomass production
Mattsson, Jim	SFU	Red cedar	Molecular markers for resistance to heartwood rot fungi and development of new strains
Murray, Brent	UNBC	Pine, Bark Beetle	Mountain Pine Beetle (www.thetriaproject.ca)
Nealis, Vince	NRCan-CFS	Spruce budworm	Incidents and impacts of viruses on spruce budworm
Plant, Aine	SFU	Spruce	Resistance to white pine weevil attack
Ritland, Kermit	UBC	Spruce, Poplar, Arabidopsis, Pine	Treenomix I and II; Conifer Forest Health (www.treenomix.ca)
Saddler, Jack	UBC		Forest products biotechnology including biofuels and bio-chemicals
Theilmann, David	Agriculture Canada	Spruce budworm	Genomics of Spruce Budworm (http://pestgenomics.org/ ⁵⁰)
Alberta			
Coltman, David	University of Alberta	Pine, Bark Beetle	Mountain Pine Beetle (www.thetriaproject.ca)
Cooke, Barry	NRCan-CFS	Pine, Bark Beetle	Mountain Pine Beetle (www.thetriaproject.ca)
Cooke, Janice	University of Alberta	White spruce, Pine, Bark Beetle	Arborea (www.arborea.ca); Mountain Pine Beetle (www.thetriaproject.ca)
Erbilgin, Nadir	University of Alberta	Pine, Bark Beetle	Mountain Pine Beetle (www.thetriaproject.ca)
Evans, David	University of Alberta	Spruce budworm	Genomics of Spruce Budworm (http://pestgenomics.org/ ⁵⁰)
Evenden, Maya	University of Alberta	Pine, Bark Beetle	Mountain Pine Beetle (www.thetriaproject.ca)
Sperling, Felix	University of Alberta	Pine, Bark Beetle	Mountain Pine Beetle (www.thetriaproject.ca)
Ontario			
Arif, Basil	NRCan-CFS	Spruce budworm	Genomics of Spruce Budworm (http://pestgenomics.org/ ⁵⁰)
Campbell, Malcolm	University of Toronto	Poplar	Poplar biotic and abiotic stress (www.csb.utoronto.ca/faculty/campbell-malcolm)
Carstens, Eric	Queens University	Spruce budworm	Genomics of Spruce Budworm (http://pestgenomics.org/ ⁵⁰)
Doucet, Daniel	NRCan-CFS	Spruce budworm	Genomics of Spruce Budworm (http://pestgenomics.org/ ⁵⁰)

Quan, Guoxing	NRCan-CFS	Spruce budworm	Genomics of Spruce Budworm (http://pestgenomics.org/ ⁵⁰)
Krell, Peter	University of Guelph	Spruce budworm	Genomics of Spruce Budworm (http://pestgenomics.org/ ⁵⁰)
Regan, Sharon	Queen's University (Dept. Biology)	Poplar	http://biology.queensu.ca/faculty/regan.html
Walker, Virginia	Queen's University	Spruce budworm	
Quebec			
Beaulieu, Jean	Canadian Wood Fibre Centre	Spruce	Association studies; participates in Arborea (www.arborea.ca)
Bernier, Louis	Université Laval	Elm	Dutch elm disease (http://www.cefc.ca/index.php?n=Membres.LouisBernier)
Bousquet, Jean	Université Laval	White spruce	Arborea II (www.arborea.ca)
Cusson, Michel	Laurentian Forestry Centre (NRCan-CFS)	Spruce budworm	Genomics of Spruce Budworm (http://pestgenomics.org/ ⁵⁰)
Hamelin, Richard	NRCan - CFS	Genomics of fungi	Participates in Tria (www.thetriaproject.ca)
Isabel, Nathalie	NRCan- CFS	Spruce	QTL mapping; participates in Arborea (www.arborea.ca)
Mackay, John	Université Laval	White spruce, poplar	Arborea I and II (www.arborea.ca)
Séguin, Armand	NRCan- CFS	Poplar and spruce	Disease resistance mechanisms
Tsang, Adrian	Concordia University	Fungi	Centre For Structural and Functional Genomics: forest/wood, biofuel, and industrial enzyme applications (http://gene.concordia.ca/csfg/home/aboutus.html ; www.concordia.ca/about/whoware/tellingourstories/research/tsang.php)
Atlantic Provinces			
Beardmore, Tannis	NRCan - CFS	Spruce, hardwood species	Tree seed biotechnology

Lucarotti, Chris	NRCan - CFS	Viruses	Registered balsam fir sawfly virus; scientific leader for Sylvar Technologies
Rajora, Om	University of New Brunswick	Spruce	Forest and Conservation Genomics and Biotechnology (www.unb.ca/news/expert/ex_expert.php?expid=878).